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A T O M I Z A T I O N O F L I Q U I D F U E L S

By Dr. R. Kuehn

PART II

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FUELS TESTED

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ATOMIZATION

From "Der Motorwagen," October 10 and 20, and November 30, 1924.

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ATOMIZATION OF LIQUID FUELS.*

By Dr. R. Kuehn.

PART II.

Description of Apparatus.

The experiments were performed in the engine laboratory of the Danzig Technical High School. I am exclusively indebted to the head of this institution, Dr. R. Plank. for being able, in spite of many difficulties, to carry them to a successful termination. Dr. Plank promoted my work in every way and constantly supported me by word and deed. For the fuel nozzle employed in the experiments, I am indebted to Dr. Noé, General Manager of the Danzig shipyard, who placed it at my disposal for the entire period of the experiments. This nozzle belongs to a 15 HP. hot-bulb engine, which was built by the Bergedorfer Engine Works as a one-cylinder two-stroke-cycle ship engine and had already successfully undergone the bench test.

Fig. 2 shows the design of the nozzle. It is open, i.e., without any compulsory or automatic stop-valve. The fuel injection is regulated simply by the pressure and the adjustment of the fuel pump. For the experiments, a cock was inserted

* From "Der Motorwagen," Oct. 10, Oct. 20 and Nov. 30, 1924. For Part I, see N.A.C.A. Technical Memorandum No. 329.

before the nozzle. The mouth-piece of the nozzle was examined under the microscope, both from the outer and inner side. The diameter of the nozzle bore was turned eight times, each time about 22.5° as measured on a scale, whereby its magnitude in divisions of the scale gave

36 - 36 - 36 - 36.5 - 36.5 - 36 - 36 - 36,

or an average of about 36. The measurements showed that the nozzle bore had a very accurate circular shape. Its orifice was smooth and very slightly rounded. The scale of the microscope was found by measurement to have 68 divisions to a millimeter. The mean diameter of the bore is therefore $d = 36 \times \frac{1}{68} = 0.5292$ mm or approximately 0.53 mm. Its cross-sectional area is accordingly $f = \frac{\pi \times 0.5292^2}{4} = 0.219953$ mm², or about 0.22 mm².

In the nozzle there is an atomizer with two spiral grooves of 1" pitch designed to produce the centrifugal motion necessary for giving the fuel jet the shape of a strongly divergent cone. For comparative experiments, I had two other atomizing rods made: rod No. 2 with two grooves having a pitch of 0.5" and rod No. 3 with three grooves having a pitch of 0.5". Into the tube, which connects the nozzle to the fuel pipe or to the regulating cock, a wire-gauze strainer was introduced, which proved to be absolutely necessary, as will be shown in the subsequent description of the experiments. The strainer has a cylindrical part made of narrow-meshed brass-wire gauze

over which a linen cover is drawn. The nozzle was provided with an end-piece pointing downward, in order to obtain a conical spray affected as little as possible by the force of gravity.

The separation of the drops from the spray cone was accomplished by a sort of shutter. A large number of preliminary experiments had to be made before this was perfected. Originally it was intended to locate the shutter immediately above the pad for catching the drops, after the manner of the focal-plane shutter in a photographic camera. Experiments with a provisional shutter of this kind showed that the question of the shutter was closely connected with another question, as to what distance from the nozzle the drops should be caught. If this distance is small, the drops are so close together on the pad that they cannot be counted. As the distance is increased, the ratio of the smaller to the larger drops caught on the pad diminishes, due to the greater retardation of the former. Moreover, there is danger of the smallest drops being deflected and carried away by eddies, as their velocity decreases. Hence a less perfect picture of the atomization is obtained on the pad, the farther it is from the shutter. By its friction with the air, the shutter generated eddies, which were so violent with respect to the velocity of the finer drops, that the latter were carried away and did not reach the pad. We had to conclude, therefore, that the best

place in the jet to apply the shutter was where the velocity of all the drops was the most uniform and where the velocity of the jet was the largest as compared with the velocity of the shutter. This was confirmed by numerous changes of the distance, both of the pad and of the shutter, from the nozzle during the preliminary experiments. It was also demonstrated that the picture of the atomization on the pad was clearer, the nearer the shutter was to the nozzle. Hence, in the final arrangement, the shutter was located close to the nozzle, the pad being situated about 600 mm below the nozzle. This was the shortest distance, even at the higher atomization pressures, which rendered it possible to count the drops.

The shutter was made like a focal-plane shutter with adjustable speed and width of slot. It was operated by an electric motor, which rendered it possible to obtain the same exposure time in different experiments.

A diagram of the arrangement of apparatus is shown in Fig. 3. The atomization pressure is generated by a small pump having a piston diameter of 12 mm and a stroke of 16.5 mm and which can be operated either by hand or by a small electric motor. In the latter case, the R.P.M. can be increased to about 250, thereby delivering about 6 cm^3 per second. The pump pressure starts a piston which is weighted and keeps the atomization pressure constant. The pressure piston is exchangeable and can be either a large piston of 20 mm diameter

with a weight of π = 3.14 kg or a small piston of 10 mm diameter and a weight of $\frac{\pi}{2}$ = 1.57 kg. There are, accordingly, two sets of weights, the large ones weighing 2.5 π kg = 7.85 kg and the small ones π kg = 3.14 kg. The atomization pressures are accordingly; for the large piston,

Without weights,	1 kg/cm²,
for each small weight,	1 " ,
" " large "	2.5 " ;

for the small piston,

without weights,	2 kg/cm²,
for each small weight,	4 " ,
" " large "	10 " .

The large pressure piston generates atomization pressures up to 16-20 kg/cm². This is generated by hand-pumps up to its maximum, which is limited by a device for locking the cock to the air chamber. If the cock before the fuel nozzle is then opened, the time in which the piston falls (through the flowing of the fuel out of the nozzle) to its lowest position (a distance of 150-180 mm) suffices to set the shutter in operation and to catch the drops. When, however, higher pressures are employed, neither the weight of the large piston nor its time of fall suffices for the performance of the experiment and hance the small piston must be used and an air chamber introduced. A compression cylinder of 12 liters capacity serves as the air chamber. It serves a double purpose. Since, after

opening the nozzle cock, the small pressure-piston descends faster than the large one, the fuel must be constantly pumped during the experiment. The pump is therefore operated by an electric motor. Thereby the pump strokes tend to produce a jerky spraying from the nozzle, which is, however, entirely equalized by the air chamber. Moreover, the air chamber assures a constant atomization pressure for the duration of each experiment, even when, at the maximum applied pressure, the pumping no longer fully suffices to keep the pressure piston in motion during the whole duration of the experiment. From the air chamber to the nozzle cock, there is first a copper tube 520 mm long by 4 mm inside diameter and then a copper tube 1150 mm long by 3.5 mm inside diameter. The latter tube had already been employed in the hot-bulb engine as the pressure tube from the fuel pump to the nozzle. The nozzle can be lowered by means of suitably calibrated disks until it is close to the shutter. Fig. 4 includes a diagram of the shutter. It consists of two opposite parallel plates with well-sharpened edges. The distance between the plates, i.e., the width b of the slot, can be accurately regulated from about 5 mm down to 0 by the introduction of calibrated strips of paper. The originally rectilinear motion of the first slot model employed in the experiments has been changed into a circular motion. The shutter has two journals on which it rests, in order to keep the friction as small as possible and to simplify its op-

eration. It is operated by an electric motor (Fig. 5) which sets the shaft E in motion by means of a cord and pulley. An overhung crank on the shaft E sets the lug A in oscillation by means of a connecting rod. The latter rests on a lever, on the end of which the rotatable cam B is fastened. The front journal of the shutter is extended outward from the shutter housing and carries, on the outside, the cam C. Before the experiment, the shutter is set to the right (Fig. 4) by means of the hand-lever attached to the cam C. If, after the nozzle cock is opened, the hand-lever D is lowered, then the cam B, as soon as it swings to its right-hand position, is turned downward by means of a projection on the handle D. When the cam B again swings back toward the left, it strikes against the cam C and carries the latter along with it. The cam C immediately starts the shutter, which passes from right to left under the nozzle, whereby a very small portion of the jet passes through the slot and is caught on the pad below.

If the driving shaft E has an R.P.M. of n, then the peripheral velocity of a point of the journal with the radius r:

$$v = \frac{2 \pi r n}{60}$$

Let c' denote the speed of the journal A. At the moment when the cam B encounters the cam C, c' attains an approximate maximum of

$$c'_{max} \text{ (for } \alpha + \beta = 90^{\circ}) = \frac{v}{\cos\beta} = \frac{2\pi r n}{60 \cos\beta}$$

The cam B, on encountering the cam C at a point which, on account of the erosion of cam B, is about 0.5 mm from its lower edge, has a velocity of

$$c'' = c'_{max} \frac{(74.0 - 0.5)}{30}$$

which it transmits by the impact to the cam C. The velocity, thus imparted to the slot as it passes under the nozzle, is

$$c = c'_{max} \frac{(74.0 - 0.5)\ 96.5}{30\ (26.2 - 2.2)}$$

Now $\tan\beta = 13.75/177 = 0.078$ and hence $\beta = 4^{\circ}\ 30'$ and $\cos\beta = 0.997$. After substituting the values for c'_{max} we accordingly obtain

$$c = \frac{2\pi\ 13.75 \times 73.5 \times 96.5}{60 \times 0.997 \times 30 \times 24} n = 14.2\ n \quad \text{mm/sec.}$$

$$c = 0.0142\ n \quad \text{m/sec.}$$

If the width of the slot b is measured in mm, the time of exposure is

$$t = \frac{b}{1000c} = \frac{b}{14.2\ n} \quad \text{sec.}$$

The revolution speed n of the driving pulley or shaft E can be changed by means of a speed regulator in the circuit of the electric motor. The revolution speeds n corresponding to the different contact positions of the regulator were measured by means of a stop watch, the mean results being: for contact

No. 0.5, n = 15.5; No. 1, n = 65.2; No. 3, n = 76.2; No. 9, n = 87.7.

The trajectories of the individual oil drops in the atomization cone diverge from a point inside the nozzle orifice. Therefore, with increasing distance from the nozzle, the distance between the drops increases and correspondingly fewer drops pass through the slot. Consequently, the quantity of oil passing through the slot during the time of exposure, in proportion to the amount of oil leaving the nozzle during the same period is smaller, the greater the distance between slot and nozzle. If, however, the slot is so close to the nozzle that its width suffices to let the whole jet through, then the quantities of oil, passing through the nozzle and shutter during the exposure time, are nearly equal. This case was approximately attained in our experiments, since, on the one hand, the nozzle was so close to the shutter as to leave a play of not more than 0.2 mm and on the other hand, the minimum width of the slot was at least 0.55 mm greater than the diameter of the nozzle bore.

For the various slot widths employed in the experiments, the corresponding exposure periods are given in the following table in terms of the slot speed or contact positions of the speed regulator of the electric motor.

Contact No.	Revolution Speed	Slot speed C_{max} m/sec.	Exposure periods in seconds for various widths of slot.		
			1.75 mm	1.50 mm	1.25 mm
1/2	15.5	0.22	0.0080	0.0068	0.0057
1	65.2	0.93	0.0019	0.0016	0.00135
3	76.2	1.08	0.0016	0.0014	0.00115
9	87.7	1.25	0.0014	0.0012	0.0010

Contact No.	Revolution Speed	Slot speed C_{max} m/sec.	Exposure periods in seconds for various widths of slot.		
			1.00 mm	0.75 mm	0.55 mm
1/2	15.5	0.22	0.0045	0.0034	0.0025
1	65.2	0.93	0.0011	0.0008	0.0006
3	76.2	1.08	0.00095	0.0007	0.0005
9	87.7	1.25	0.0008	0.0006	0.00044

As already mentioned, it was necessary for the slot to pass as close as possible to the nozzle, in order to limit any disturbance of the jet to the smallest possible amount. A series of preliminary experiments demonstrated that this was eminently successful. The greatest danger seems to be that the shutter may exert a further atomizing effect on the jet. In this connection, small portions of the jet can be regarded from the following viewpoints. The jet, issuing continuously from the nozzle, is afforded the opportunity to pass through the slot only for a very brief interval of time. All portions

of the jet, leaving the nozzle either sooner or later, strike on the shutter and remain in the shutter housing. A further portion of the jet, in passing through the slot under the nozzle, strikes on the edges of the slot and some of the drops are forced through the slot. It was demonstrated, in the subsequently described experiments on the striking of the fuel jet on firm surfaces and their edges, that the oil drops, as soon as they strike an object, cling to it for the most part and only a small portion rebound. This never occurs exactly at the angle of incidence, but the drops are very strongly deflected in the direction of the deflecting surface. It follows, even if the drops which strike on the edges of the shutter should undergo further atomization, that their velocity would be so greatly diminished and they would be so strongly deflected by the velocity and direction of the slot edges, that there is no danger that many of them would reach the receiving pad (600 mm vertically below the nozzle) and materially affect the atomization picture. Lastly, there is the portion of the jet which passes unimpeded through the slot, without touching its edges. The shutter can have no effect on these drops aside from a deflection from the direction of fall, which might be occasioned by air eddies produced by the motion of the shutter. Since, however, the exit velocity of the jet is about a hundred times as great as the velocity of the shutter, this deflection can cause no measurable change in the drops. On the other hand, as soon as the slot

is narrowed or the shutter speed increased, the number of large drops in proportion to small ones, passing unimpeded through the slot, will naturally decrease, since the former, on account of their size, can be more easily hit by an edge of the slot. As a matter of fact, somewhat smaller mean values for the size of the drops were obtained in all the experiments with shorter exposures. Even for the minimum width of slot, however, these diminished values never leave the zone of the other values. In order to make absolutely sure that no one-sided shifting of the experimental results occurred, both the width of the slot and the shutter speed were frequently changed during every series of experiments.

The above facts were established by a whole series of special comparative experiments both with and without the shutter. In fact, the whole width of the jet was caught on a large unsized sheet of paper at various atomization pressures and distances and for very short periods of time. In one experiment the shutter was removed and the jet was produced by a sudden opening and immediate closing of the fuel cock. In another experiment, with a continuous jet, the shutter was opened and closed several times in rapid succession, until about the same amount of fuel had been caught on the pad as in the experiment without the shutter. A comparison of the two pictures, with reference to the distribution, closeness and size of the drops, showed no noticeable differences, which

could have been produced by the shutter, aside from a characteristic core of large closely-laid drops in the middle of the picture produced by opening and closing the cock, which was due to subsequent dripping from the nozzle and was naturally lacking in the picture obtained with the shutter.

Hence, after the utility of the final form of the shutter for our experiments had been demonstrated, we had to solve the problem as to the best method for catching the drops, in order to be able to weigh and count them without excessive errors. For the small weights here involved, the total weight found will be less affected by difficultly determined factors, such as hygroscopy of the receiving pad and errors in reading the balance, the greater the total weight of the drops and hence the greater the number of drops caught. On the contrary, the drops can be counted more easily and accurately, the smaller their number and the more visible they are rendered. The size and properties of the pad for catching the drops must be adapted to these contrary viewpoints. Any pad with an impenetrable surface is not suitable for this purpose, because it allows the drops to run together and affords no means for rendering them sufficiently visible. Moreover, there is danger of rebounding from a smooth solid surface. It is therefore necessary to employ an absorbent surface, although the latter has the great disadvantage of itself undergoing fluctuations in weight through the absorption and evaporation of atmospheric

moisture, which, under certain conditions, can amount to more than the weight of the drops and seriously impair the reliability of the experimental results. In testing pads made from all kinds of materials (especially paper of varying thickness, hardness, smoothness and colors), it was found that they were all more or less unsuited to our needs, because the drops could not be seen plainly enough on them for counting. Smoked glass was found to be the best. The drops spread relatively little in the layer of soot, show a well-defined round edge and a clear transparent center which contrasts well with the black smoked surface. A necessary condition, however, is that the layer of soot must be uniform and fine grained. Soot from burning benzol or turpentine will not do, because it has much too coarse flakes, in which the smallest drops vanish. The glass plates can be suitably smoked, however, with a small benzine or kerosene lamp having an adjustable flame, so that the smallest drops are clearly visible on looking through the glass toward an illuminated white surface. Of the glass plates employed, Nos. 1-11 and 15-16 were 9×12 cm; Nos. 12-14 were 8×8 cm. Their weights in mg were as follows:

1 - 24774.2	5 - 26540.0	9 - 28245.3	16 - 29578.4
2 - 24905.2	6 - 26816.3	10 - 28310.8	12 - 16564.3
3 - 25987.6	7 - 27425.3	11 - 28967.1	13 - 20598.2
4 - 26052.6	8 - 27790.9	15 - 29327.4	14 - 22654.4

Fuels tested.- The experiments were instituted with gas oil and kerosene. Both were petroleum distillates from Galicia which are well suited for driving internal combustion engines. For comparison, a few supplementary experiments were tried with lubricating oil, a considerably heavier and more viscous liquid. These liquids were found to possess the following physical characteristics:*

1. Gas oil at a mean temperature of 19°C.

Specific gravity	$\gamma = 0.852$
Mass density	$\rho = \gamma/g = 0.00087$ g sec.^{2}/cm^4
Capillarity	$\alpha = 2.85$ mg/mm
Kinematic capillarity	$\kappa = \alpha/\rho = 32.8$ cm^3/sec.^{2}
Viscosity	$\eta = 0.0000645$ g-sec./cm^2
Kinematic viscosity	$\upsilon = \eta/\rho = 0.074$ cm^2/sec.

2. Kerosene at a mean temperature of 18.6°C.

Specific gravity	$\gamma = 0.812$
Mass density	$\rho = \gamma/g = 0.00083$g sec.^{2}/cm^4
Capillarity	$\alpha = 2.7$ mg/mm
Kinematic capillarity	$\kappa = \alpha/\rho = 32.6$ cm^3/sec.^{2}
Viscosity	$\eta = 0.00001$g sec./cm^2
Kinematic viscosity	$\upsilon = \eta/\rho = 0.023$ cm^2/sec.

* For the accurate determination of these characteristics with relation to the temperature and their representation by curves, see Kuehn, "Dissertation," Danzig Technische Hochschule, 1924, No. 6.

3. Lubricating oil at a mean temperature of 19°C.

Kinematic viscosity $\nu = \eta/\rho = 2.7$ cm²/sec.

On comparing gas oil and kerosene, we find that the surface tension of both liquids is about the same. The kinematic viscosity of gas oil is, however, more than three times as great as that of kerosene.

A. Atomization experiments.- The drops were weighed on a balance from the organic-chemistry laboratory of the Danzig Technical High School. It was a precision balance having a rider scale with 2 mg divisions. After a little practice, readings could be made with an error of less than 0.05 mg. It was found that freshly smoked glass plates increased considerably in weight for quite a long time, by absorbing moisture from the air, but that plates, which had been kept in the laboratory for a number of hours after being smoked, lost a little in weight after being introduced into the balance case. This loss in weight was due to the presence of concentrated sulfuric acid which made the air in the balance case drier than in the rest of the laboratory. Moreover, the experiments were performed in a relatively dark room, so that the balance had to be lighted with an electric lamp, which caused a slight heating and consequent drying of the layer of soot. The loss in weight of the air-dried layer of soot in the balance case was relatively small, did not last long and was fairly constant. On the contrary, the weight increase of the fresh-

ly smoked plates was considerable. Consequently they were not used in the experiments for some time (usually more than 24 hours) after they were smoked. Use was made of only those plates which had received a perfectly uniform and fine-grained deposit of soot. After such a plate had been laid on the balance and tared, it was left lying (at least half an hour) until its weight neither increased nor decreased and then a rider reading was taken. In the meantime the fuel pump and shutter were started. As soon as the desired atomization pressure was attained, the plate was removed from the balance and laid on the frame under the shutter. Then the fuel cock was opened and the shutter was released during the down stroke of the pressure piston. The plate was then promptly returned to the balance and a stop watch started. The temperature of the oil, as it left the nozzle, was also taken. The experiment was so conducted as not to take over 60 seconds, nor under 50 seconds from the time the plate was removed from the balance till it was returned to the same. The second weighing of the plate was made between 2 and 3.5 minutes after the return of the plate to the balance and in such a manner that the rider was moved until, within the said time limits, the swing of the balance was the same on both sides of the zero point. The first weighing of the plate without the droplets was obtained within the same time limits and

in the same manner as the second weighing.

At the instant this occurred in the second weighing, the watch was stopped and both the weight and the time consumed were determined from the readings of the balance and of the watch. Then the plate was removed from the balance and the drops counted. The counting could not be long delayed, since the oil spots made by the finest drops soon became indistinguisgable. The difference between the balance readings before and after the exposure gave only the apparent total weight G_s of all the drops. This weight had to be corrected.

While the plate was under the shutter, the layer of soot, which lost a little weight in the balance case during the first weighing, again had the opportunity to absorb moisture from the air, so that, during the exposure, it again took on weight from this cause. The amount of moisture thus absorbed is a function of the time during which the plate is exposed to the action of the air in the laboratory, the nature of the layer of soot (its thickness, porosity and absorptivity) and the condition of the air (its temperature and humidity). Furthermore, the amount of moisture absorbed is proportional to the area of the layer of soot. If the weight of the moisture absorbed per square centimeter is G_l and the area of the plate is F, then the total weight of moisture absorbed is FG_l.

As soon as the plate, after catching the drops, is returned to the balance for the second weighing, the absorbed moisture begins to evaporate in the drier air, causing the plate to lose in weight. This loss is: (1) proportional to the area of the smoked surface F; (2) approximately proportional, at the beginning, to the time τ_1; (3) approximately proportional to the weight absorbed (G_l k_1), k_1 being an evaporation factor which gives the weight loss in mg for each mg of the weight originally absorbed per minute and which equals $F\ G_l\ k_1\ \tau_1$.

The total change in the weight of the plate due to the hygroscopicity of the soot is therefore $F\ G_l - F\ G_l\ k_1\ \tau_1 = F\ G_l\ (1 - k_1\ \tau_1)$. The weight increase G_l and the weight decrease k_1 were determined experimentally. Since it was not always practicable to determine these simultaneously with the weight of the drops for one and the same plate, a few plates were taken from the set prepared for weighing the drops and subjected to special tests, which simply served to establish the effect of humidity and temperature on the weight of the plates. These tests were distributed over the whole period of the weight determinations of the drops. In winter the experiments were conducted in a well-heated room where the temperature and humidity of the air remained practically constant. The changes in weight did not, therefore, vary greatly among themselves and consequently the mean values obtained from these tests were employed for correcting the weights of the drops.

Then it only remained to make a simultaneous determination of the temperature and humidity of the air in connection with each individual determination of the size of the drops. The plates used for determining the correction necessitated by the humidity were, after the first weighing, left one minute under the shutter and then weighed again. This corresponded to the procedure in catching the drops, in which each plate was allowed to remain under the shutter as closely as possible to one minute. In this way, the effect of the time on the determination of the weight increase was eliminated. The second weighing was then conducted in the following way: The balance rider was successively moved to correspond to subsequent decreases of the original increases in weight of 0.35, 0.25, 0.15 and 0.05 mg to obtain readings for 0.30, 0.20 and 0.10 mg decrease in weight and at each weight, as soon as the balance pointer swung equally to the right and left of the zero position, note was made of the time elapsed since the introduction of the plate into the balance case. The results of these tests are shown graphically in Figs. 6 and 7.* These figures give us the weight increase caused by the absorption of moisture under the shutter, which increase is subsequently diminished by evaporation in the balance case.

As already mentioned, the weighing of the plates sprayed with the oil drops always took place between 2 and 3.5 minutes

* See Kuehn, "Dissertation," Danzig T. H., 1924, No. 6, Tables 1311-1360, On pages 76-78.

after the spraying. For this interval the evaporation of the atmospheric moisture absorbed by the soot is assumed to be proportional to the time elapsed, which is allowable on account of the approximately rectilinear course of the vaporization curves during this interval. If, therefore, a straight line is drawn through two points of the curve corresponding to the times $\tau = 2$ and $\tau = 3.5$ minutes, which straight line cuts off the distance A on the axis of the ordinates and the distance B on the axis of the abscissas, then, according to the equation of a straight line, the weight of the moisture remaining after the weighing time τ_1 is $F\,G_l(1 - k_1\,\tau_1) = A\,(1 - \tau_1/B)$. Thereby, for the above assumption, $A = F\,G_l$ and $B = 1/k_1$ and hence G_l and k_1 can be determined, in an approximation corresponding to this assumption, directly from the points of intersection of the straight lines with the axes of the coordinates. The mean values, $G_l = 0.003886$ mg and $k_1 = 0.1664 \frac{\text{mg}}{\text{mg} \times \text{min}}$, resulting from all the vaporization tests were employed in determining the weight of the drops. If the difference in the balance readings, before and after the plate is sprayed with oil, gives an apparent oil weight G_S, then the real weight of the oil at the moment of weighing is $G_W = G_S - F\,G_l\,(1 - k_1\,\tau_1)$.

The actual weight of the oil drops at the time of weighing is, however, a little less than the weight G_k of the oil sprayed on the plate, since some of it has evaporated in the interval between the spraying and the weighing. Hence, another

weight correction must be made. After the oil is sprayed on the plate, the plate is left 20-30 seconds (τ_2) under the shutter, before being transferred to the balance case, where it is weighed after 2-3.5 minutes (τ_1). Accordingly there elapses a time interval of $\tau_2 + \tau_1 = 2.5$ to 4 minutes. During this interval some of the oil evaporates, the weight of which must be determined.

The oil drops are absorbed by the soot on the plate and form disks, whose height is the thickness of the soot. The evaporation goes on from the top of these disks and is, in general, proportional to the area and the time. Its rapidity depends also on the temperature and humidity of the adjacent air. The area of the drops absorbed by the soot and exposed to the air is not known, since this area depends not only on the volume of the drops, but also on the thickness of the soot. Moreover, in this case, the evaporation is proportional to the time only in the first moment since, after the evaporation of the topmost layer, the succeeding layers, which lie successively deeper in the soot, are correspondingly better protected from evaporation, so that it takes place very slowly. The correction factor for determining the correct oil weight must therefore be determined experimentally. For this purpose, special experiments were undertaken on the evaporation of the oil drops from glass plates, smoked and unsmoked. It was found that evaporation was much slower in the former case, first, because the oil drops did not spread so rapidly as on the smooth

glass and, secondly, because the drops were better protected from evaporation by the soot. In order to eliminate, in these experiments, every effect which changes in the temperature and humidity of the air might have on the weight of the glass plates with their sensitive coats of soot, each plate was left on the balance pan from the beginning to the end of the experiment. The first weighing was made about an hour after the plate was placed on the balance and after it had ceased to show any increase or decrease in weight. Then a small drop of oil was sprayed on the plate from a pipette, a stop watch was started, the weight of the drop counterbalanced by moving the rider and the time noted. Then the rider was moved back, space by space, to correspond to the loss in weight from the evaporation of the oil and, at each division, a record was made of the time elapsed since the dropping of the oil on the plate. The results of these experiments are shown by the curves in Figs. 10-11, in which the decrease in weight of the drops of gas oil or kerosene is plotted against the time elapsed.*

If these vaporization curves are extended to the left to their point of intersection with the axis of the ordinates, we obtain, for the time $\tau = 0$, the corrected weight G_k of the oil actually sprayed. If, after the time interval $\tau_2 + \tau_1$ the oil weight is G_w, then the loss in weight from the evaporation of the oil is $k_2 = \frac{G_k - G_w}{G_{k_2}(\tau_2 + \tau_1)}$ per unit of the origi-

* See Kuehn, previous reference, Tables 1361-1400, on pp. 85-87.

nal weight and time.

If, from all the vaporization curves, we compute a mean value k_2, we then obtain a factor which will enable us to make an approximate correction of the weight, without needing to know the area of the exposed surface of the absorbed oil drops or the thickness of the layer of soot. This factor covers the mean effect of the temperature and humidity of the air on the evaporation of the oil drops in all the experiments and can therefore be employed for correcting the weight of the drops in all atomization experiments. The computation is thereby greatly simplified. The approximation, thus effected, is entirely satisfactory, since the necessary correction, corresponding to the extremely small loss in weight of the oil from evaporation, is much smaller than the correction for the effect of humidity on the weight of the layer of soot. The total weight, lost by the drops through evaporation, is $G_k - G_w = k_2 G_k (\tau_2 + \tau_1)$, from which we obtain $G_k = \frac{G_w}{1-k_2(\tau_2+\tau_1)}$, as the initial weight of the drops.

After every vaporization curve in the domain of the first 3-4 minutes had been replaced by a straight line, we computed, for this region, the value k_2, i.e., the loss of weight in mg for the evaporation of the oil for 1 mg of the initial weight of all the drops and 1 min. of the evaporation time. The mean value, from all the vaporization curves, was: for gas oil, $k_2 = 0.003467 \frac{mg}{mg \times min}$; for kerosene, $k_2 = 0.0462 \frac{mg}{mg \times min}$.

The mean values differ but little from the separate values obtained for each curve and hence this simplification of the computation is entirely justified. A further simplification should be made with respect to the time. In fact, a mean weighing period of τ_1 = 2 min. 50 sec. should be employed for all atomization experiments, in order to facilitate the evaluation of the measurements of the drops. Since the actual weighing time does not differ more than 2/3 min. from this assumption, the maximum error in the determination of the evaporated weight, based on an original weight of 1 mg, is, for kerosene, $\pm 0.0462 \times \frac{2}{3} = \pm 0.0308$, or about 3% of the weight of the drops. For gas oil the maximum error is only $\pm 0.003467 \times \frac{2}{3} = \pm 0.00231$, or about 1/4% of the weight of the drops, showing that this simplification in the time determination is allowable. In the atomization experiments, the plates remain under the shutter for about 30 seconds (τ_2) after the absorption of the drops, before being transferred to the balance case. Under the shutter the evaporation of the oil proceeds more slowly than in the balance case, because the air is drier in the latter. Since the value of k_2 could be accurately determined only for the time during which the drops were inside the balance case, but must be taken into account for the whole evaporation period, the time elapsed under the shutter is accordingly reduced, to take account of the slower rate of evaporation, to 20 seconds.

This gives us 20 sec. + 2 min. 50 sec. = 3 min. 10 sec. as the total evaporation time $(\tau_2 + \tau_1)$ to be employed in the computations.

From the equations $G_k = \frac{G_w}{1 - k_2 (\tau_2 + \tau_1)}$ and $G_w = G_s - F\, G_l\, (1 - k_1\, \tau_1)$ we obtain, as the actual or corrected weight of all the oil drops caught on a plate,

$G_k = \frac{G_s - F\, G_l\, (1 - k_1\, \tau_1)}{1 - k_2\, (\tau_2 + \tau_1)}$, in which:

G_s = apparent weight of the drops, taken as the difference in the balance readings;

F = area of the plates = 108 cm^2 for 9 x 12 plates, 64 cm^2 for 8 x 8 cm plates;

G_l = weight of absorbed atmospheric moisture per cm^2 of soot surface = 0.003886 mg/cm^2;

k_1 = vaporization factor of the absorbed moisture = 0.1664;

τ_1 = measured weighing time;

k_2 = vaporization factor: for kerosene, 0.0462; for gas oil, 0.003467;

$\tau_2 + \tau_1$ = evaporation time = 3 min. 10 sec.

Table I.

Atomization of gas oil. Nozzle, with old atomizer. Distance 600 mm

No.	Pressure kg/cm²	Plate No.	Motor contact No.	Slot width mm	Exposure sec./1000	Temp. of oil °C	Number of drops
49	23	1	9	1.5	1.2	17.7	4100
50	23	2	9	1.5	1.2	17.7	7500
51	24	8	3	1.0	0.95	16.7	1300
52	24	10	3	1.0	0.95	16.6	3500
53	24	14	3	1.0	0.95	16.5	9400
54	26	9	3	1.0	0.95	16.5	1060
55	26	6	3	1.25	1.15	18.9	2200
56	26	8	3	1.25	1.15	19.7	1700
57	26	13	3	1.25	1.15	19.7	19000
58	26	14	3	1.25	1.15	19.6	2500
59	30	4	1	1.25	1.35	20.3	11900
60	30	13	3	1.25	1.15	17.3	12600
61	30	14	3	1.25	1.15	18.3	3700
62	30	5	3	1.25	1.15	18.7	1200
63	34	1	9	1.75	1.4	18.8	5800
64	34	3	9	1.75	1.4	18.9	7700

Table I (Cont.)

Atomization of gas oil. Nozzle, with old atomizer. Distance, 600 mm

No.	Balance reading before mg	after mg	difference mg	Weighing time min.	Corrected weight mg	Drop size Weight mg	Diameter mm
49	-1.10	+0.85	1.95	3.0	1.758	0.000429	0.0985
50	-0.45	+2.30	2.75	2.3	2.534	0.000338	0.091
51	-2.60	-1.85	0.75	2.4	0.522	0.000401	0.0965
52	-2.70	-1.75	0.95	3.2	0.771	0.000220	0.079
53	-1.05	+1.00	2.05	3.0	1.947	0.000207	0.0775
54	-7.30	-6.95	0.35	3.3	0.176	0.000166	0.072
55	-0.05	+0.65	0.70	2.5	0.483	0.000219	0.079
56	-4.30	-3.55	0.75	2.3	0.510	0.000300	0.0875
57	-4.00	-0.60	3.40	3.2	3.325	0.000175	0.073
58	-1.10	+0.05	1.15	3.1	1.044	0.000418	0.098
59	-6.55	-3.55	3.00	2.5	2.810	0.000236	0.081
60	-3.60	-1.55	2.05	3.2	1.960	0.000155	0.070
61	-7.90	-6.80	1.10	3.0	0.986	0.000266	0.084
62	-7.00	-6.55	0.45	3.3	0.278	0.000232	0.0805
63	-5.10	-3.95	2.15	2.4	1.937	0.000334	0.0905
64	-2.30	-0.70	1.60	3.1	1.416	0.000184	0.0745

Table II.

Atomization of kerosene. Nozzle, with old atomizer. Distance 600 mm

No.	Pressure kg/cm²	Plate No.	Motor contact No.	Slot width mm	Exposure sec./1000	Temp. of oil °C	Number of drops
314	28	8	9	0.55	0.44	19.1	3000
315	28	10	9	0.55	0.44	19.3	10300
316	28	14	1	0.55	0.6	19.2	3100
317	30	15	9	0.55	0.44	17.1	6300
318	30	13	1	0.55	0.6	17.2	7200
319	30	14	1	0.55	0.6	17.2	4400
320	30	1	9	0.55	0.44	17.6	7600
321	32	4	9	0.55	0.44	18.8	4400
322	32	5	9	0.55	0.44	19.9	8200
323	32	13	1	0.75	0.8	16.7	9600
323	32	1	9	0.75	0.6	17.1	9700
324	34	5	1	0.55	0.6	16.7	15400
325	34	6	9	0.55	0.44	16.6	8900
326	34	8	9	0.55	0.44	16.8	2500
327	34	9	9	0.55	0.44	16.8	14800
328	34	10	9	0.55	0.44	16.7	7600

Table II (Cont.)

Atomization of kerosene. Nozzle, with old atomizer. Distance 600 mm

No.	Balance reading before mg	after mg	difference mg	Weighing time min.	Corrected weight mg	Drop size Weight mg	Diameter mm
314	-9.30	-8.60	0.70	3.0	0.575	0.0001917	0.077
315	-0.25	+0.50	0.75	3.1	0.647	0.0000628	0.053
316	-9.20	-8.80	0.40	2.5	0.316	0.0001020	0.062
317	-2.60	-1.95	0.65	2.2	0.462	0.0000733	0.0555
318	-4.70	-3.85	0.85	2.3	0.828	0.0001150	0.065
319	-7.20	-6.45	0.75	2.3	0.710	0.0001613	0.0725
320	-5.75	-4.75	1.00	2.4	0.900	0.0001184	0.065
321	-7.70	-6.95	0.75	2.5	0.620	0.0001410	0.069
322	-0.55	+0.70	1.25	3.3	1.262	0.0001540	0.0715
323	-4.80	-3.95	0.85	3.1	0.861	0.0000897	0.0595
323	-7.10	-6.20	0.90	3.0	0.811	0.0000835	0.058
324	+0.25	+1.30	1.05	2.5	0.974	0.0000632	0.053
325	-4.30	-3.60	0.70	3.0	0.575	0.0000646	0.0535
326	-8.95	-8.40	0.55	2.5	0.385	0.0001540	0.0715
327	-4.45	-3.15	1.30	3.2	1.307	0.0000883	0.059
328	-8.65	-7.90	0.75	3.0	0.634	0.0000835	0.058

On substituting the numerical values in the above formula, we obtain:

I. For gas oil,

9 x 12 cm plates, $G_k = (G_s - 0.4197 + 0.0698\ \tau_1)\ 1.0111$,

9 x 8 " " $G_k = (G_s - 0.2487 + 0.0414\ \tau_1)\ 1.0111$;

II, For kerosene,

9 x 12 cm plates, $G_k = (G_s - 0.4197 + 0.0698\ \tau_1)\ 1.175$,

8 x 8 " " $G_k = (G_s - 0.2487 + 0.0414\ \tau_1)\ 1.175$.

If Z denotes the weight of all the drops on the plate, then the weight of a single drop (G) is G_k/Z. The drops are regarded as spheres whose diameter is d. The temperature varied but slightly during the experiments, so that a mean specific gravity γ can be employed in the computations. We then have $d = \sqrt[3]{\frac{6\ G}{\pi\ \gamma}}$.

For gas oil (with $\gamma = 0{,}854$ at a mean temperature of 19°C), we have $d = 1.308\sqrt[3]{G}$.

For kerosene (with $\gamma = 0.812$ at a mean temperature of 18.6°C), we have $d = 1.330\sqrt[3]{G}$.

By means of the above formulas, the results of the atomization experiments were evaluated and tabulated.* Tables I and II are here given as examples of the kind of measurements and their evaluation. The mean diameters of the drops are shown in Figs. 10-14.

* See Kuehn, previous reference, Tables 1-348, pp. 101-124.

B. Error limits.- In order to get an idea of the degree of accuracy attainable, it seems desirable to determine the error limits. We will do this in connection with experiment 346. In this atomization experiment with kerosene, the apparent weight of the drops (G_s) was found to be 0.6 mg after a weighing time of $\tau_1 = 2.835$ min. Then 9100 drops were counted on the plate. The 9 x 12 cm plate was used, so that $F = 108$ cm^2. The atomization pressure was 42 kg/cm^2. The corrected weight of all the drops is $G_k = (0.6 - 0.4197 + 0.0698 \times 2.835)\ 1.175 = 0.445$ mg. The mean weight of a drop is therefore $G = 0.445/9100 = 0.000049$ mg.

According to the rules for computing with small quantities,* if the errors are denoted by the corresponding Greek letters, we obtain, for our formula for the corrected weight (G_k) of all the drops, the following expression:

$$\frac{\mu}{G_k} = \frac{\frac{1}{k_1 \tau_1}\left(\frac{\sigma}{F\ G_l} + \frac{\lambda}{G_l}\right) \pm \left(\frac{\lambda}{G_l} + \frac{\kappa_1}{k_1} + \frac{\theta_1}{\tau_1}\right) \mp \frac{k_2 \tau_3 \left(\frac{\kappa_3}{k_2} + \frac{\theta_3}{\tau_3}\right)}{1 - k_2 \tau_3}}{\frac{1}{k_1 \tau_1}\left(\frac{G_s}{F\ G_l} - 1\right) + 1}$$

Herein, on the assumption that the following experimental errors might occur,

σ = maximum error in weighing (to obtain G_s) = $\pm$ 0.05 mg;

λ = maximum deviation of the measured value from the mean value $G_l = 0.003886$ mg:

above 0.004730 - 0.003886 = 0.000844

below 0.003886 - 0.00264 = 0.001246

$\lambda/G_l \sim 0.32$

* See Kohlrausch, "Praktische Physik," 1921 edition, p. 9.

κ_1 = maximum deviation from the measured value $k_1 = 0.1664$

above $0.1880 - 0.1664 = 0.0116$

below $0.1664 - 0.1320 = 0.0144$

$\kappa_1/k_1 \sim 0.08$

θ_1 = maximum error in the weighing time = 15 sec. or 0.25 min.

$$\frac{\theta_1}{\tau_1} \sim \frac{0.25}{2.835} \sim 0.10$$

κ_2 = maximum deviation from the measured value $k_2 = 0.0462$:

above $0.0536 - 0.0462 = 0.0074$

below $0.0462 - 0.0362 = 0.0100$

$$\kappa_2/k_2 \sim 0.2$$

θ_3 = maximum error in the estimation of $\tau_2 + \tau_1 = \tau_3$, assumed to be 20 sec. or 0.33 min.

$$\theta_3/\tau_3 = \frac{0.33}{3.167} \sim 0.1$$

If we introduce the above values, as likewise the numerical values of $F\,G_l = 108 \times 0.003886 = 0.4197$,

$$\frac{1}{k_1\,\tau_1} = \frac{1}{0.1664 \times 2.835} = 2.12 \quad \text{and}$$

$$k_2\,\tau_3 = 0.0462 \times 3.167 = 0.146$$

into the equation for μ/G_K and if we take all errors with the plus sign, in order to obtain the maximum possible error, we have

$$\mu/G_K = 0.748 + 0.0513 = 0.7993 \sim 0.8.$$

For the most unfavorable case, therefore, a maximum error of

about 80% is to be feared.

The mean weight of a single one of the z drops is

$G = \frac{G_k}{z}$; hence

$$G \pm \rho = \frac{G_k \pm \mu}{z \pm \xi} \quad \text{and} \quad \frac{\rho}{G} = \pm \left(\frac{\mu}{G_k} - \frac{\xi}{z} \right)$$

ξ being the possible error in the number of drops, due to mistakes in counting or the overlapping of the smallest drops. This error increases with the density of the distribution of the drops on the plate and hence with their number. For a small number of drops, the maximum error might attain 3-5%, while, for a very large number of drops (of over 10000), it might be as high as 10%. For our computation, we will assume that $\xi/z = 0.1$. We then have, for the most unfavorable case, when all the errors are taken with the plus sign,

$$\frac{\rho}{G} = 0.8 + 0.1 = 0.9.$$

The mean drop diameter is then

$$d = 1.33 \sqrt[3]{G} = 1.33 \sqrt[3]{0.000049} = 0.0485 \text{ mm.}$$

In the computation of the drop diameter, still another error may be caused by inexactness of the specific gravity. In the computation, the specific gravity of kerosene at 18.6°C ($\gamma = 0.812$) was employed. During the experiments, however, the temperature of the kerosene varied between 16° and 21°. The maximum errors of γ are therefore:

above $0.8138 - 0.8120 = 0.0018$

below $0.8120 - 0.8102 = 0.0018$

hence, $\frac{\chi}{\gamma} = \frac{0.0018}{0.8120} = 0.00222.$

This error is so small as to be insignificant in comparison with the other errors. Hence, in the determination of the drop diameter, errors can occur up to 90% (corresponding to $\frac{\rho}{G} = 0.9$).

At first glance, therefore, the results of the experiments seem to be very inaccurate. It is, however, very improbable that the errors in any one experiment all have the same sign. Consequently, the errors will partially offset one another and their total will be less than 90%. The experiments yield therefore considerably more than the "order of magnitudes" of the drops. If we consider, moreover, that the drops, simultaneously formed in the atomization cone, are of very different sizes, so that the mean values of several thousands of drops may differ among themselves by more than twice their size, then the above-computed errors seem entirely endurable, especially as the object of our experiments was not to obtain accurate individual values, but only the closest possible mean value by means of the largest possible number of measurements.

Discharge measurements.- In order to judge the atomization process, it is important to know the effect of the nozzle on the rate of flow and especially to study the effect of the

atomization pressure, the spiral grooves of the atomizer rod and the state of the fuel. There is some uncertainty introduced into these investigations by the fact that all the channels, through which the fuel passes to the nozzle, also affect the rate of flow. It was very difficult to eliminate this effect in the apparatus employed, so that the plan of making the investigation apply exclusively to the nozzle was abandoned. In this way, moreover, the results threw more light on the problems of practical engine operation, since the fuel delivery system employed in the experiments was essentially like that employed in real engines.

In the first preliminary experiments, it was found that, in spite of a constant atomization pressure, the rate of flow fluctuated greatly. Especially at low pressures, it was found that the rate of flow decreased considerably with the time and could then be brought back to its original rate only by employing a higher pressure for a short time. This decrease was especially noticeable in the case of gas oil and is explained by the fact that very small solid particles suspended in the oil, which one finds deposited as very fine tenacious mud at the bottom of an oil reservoir and which, in time, by continuous spraying, are deposited in front of and in the valve bore and therefore plugs it up. At low pressures, it even sometimes happens that the spray is entirely stopped and transformed into a mere dripping. In order to prevent this stopping of the spray, a strainer was introduced before the nozzle (Fig. 2).

The strainer consisted of brass-wire gauze covered with linen and it decidedly improved the outflow. The rate of flow was very uniform above 4-5 kg/cm² and showed a noticeable decrease only at the lowest pressures. The oil was caught directly in a large measuring glass, into which the nozzle was introduced through a cork stopper at the top. The cork prevented the escape of the oil drops from the glass. A long glass tube, passing vertically through the cork, afforded an exit for the air. The oil could not be measured with a pipette, because the atomization made the oil too foamy for observing its surface level. The experiments could only extend over very short periods corresponding, on the one hand, to the capacity of the measuring glass and, on the other hand, to the volume displaced by the down stroke of the pressure piston. The pressure piston was raised to its highest position, then the nozzle cock was opened and a stop watch simultaneously started. Before the piston reached its lowest position, the cock was closed and the watch stopped. For the highest pressures, the oil had to be pumped by an electric motor with the aid of an air chamber. The resulting sudden outflow of the fuel introduces an inaccuracy which must be eliminated as much as possible by many repetitions of the experiment. On the other hand, it corresponds more closely to actual working conditions and, above all, affords protection against clogging of the nozzle.

The results of the discharge measurements are shown graphic-

ally, in Fig. 15 for gas oil, and in Fig. 16 for kerosene, as plotted against the pressure with the different atomizer rods.* Let

Q = the measured volume delivered per second ($cm^3/sec.$).

p = atomization pressure ($kg\ cm^2$),

F = cross-section of nozzle orifice = 0.22 mm^2,

w = velocity of flow ($m/sec.$),

φ = coefficient of velocity,

α = coefficient of contraction,

$\mu = \alpha\ \varphi$ = coefficient of outflow or delivery,

γ = specific gravity of fuel (g/cm^3).

g = acceleration due to gravity = 9.81 $m/sec.^2$

The two following equations then hold good:

1. $w = \varphi \sqrt{\frac{2 \times 10g\ p}{\gamma}}$ ($m/sec.$); 2. $Q = \alpha\ F\ w$ ($cm^3/sec.$).

For the ideal case, when $\alpha = 1$ and $\varphi = 1$ and, hence, $\mu = 1$, we have the theoretical flow velocity $w_{th} = \sqrt{\frac{2 \times 10g\ p}{\gamma}}$ ($m/sec.$) and a theoretical discharge volume $Q_{th} = F\ w_{th}$ ($cm^3/sec.$). The discharge coefficient for the volume actually delivered is therefore, $\mu = Q/Q_{th}$. It may be safely assumed that $\alpha = 1$ for pressures of over 6-8 kg/cm^2, at which the atomization cone is already fully developed. In this case $\varphi = \mu$ and we have $w = \mu\ w_{th} = Q/F$ for the discharge velocity.

* See Kuehn, previous reference, Tables 349-1310, pp. 135-157.

For gas oil,

$$w_{th} = \sqrt{\frac{2 \times 10 \times 9.81}{0.854}}\, p = 15.16 \sqrt{p} \text{ m/sec.}$$

$$Q_{th} = 0.22 \times 15.16 \sqrt{p} = 3.335 \sqrt{p} \text{ cm}^3/\text{sec.}$$

For kerosene,

$$w_{th} = \sqrt{\frac{2 \times 10 \times 9.81}{0.812}}\, p = 15.54 \sqrt{p} \text{ m/sec.}$$

$$Q_{th} = 0.22 \times 15.54 \sqrt{p} = 3.419 \sqrt{p} \text{ cm}^3/\text{sec.}$$

By means of these equations and the measured values of Q, we computed μ and w, which are plotted against the pressure in Figs. 17-20.

Atomization.- This is best accomplished by gradually increasing the pressure from a very low value and simultaneously observing the fuel jet. We shall therefore try to describe the changes undergone by the jet as the pressure is increased (Fig. 21).

At very small pressures, there is no continuous flow, but only a dripping from the nozzle, slow at first and then faster, as the pressure is gradually increased, until a fine continuous stream is produced (Fig. 21A). The latter has, at first, at the nozzle orifice, a characteristic cup-shaped beginning (A_1), below which there is a sharp contraction and the stream becomes very small and has a perfectly smooth surface. With a further slight increase in the pressure, the contraction diminishes; the stream becomes larger; the cup-like enlargement

at the nozzle disappears and the outflow assumes the form A_2. For a distance of L_1 from the nozzle, the stream is fully closed, has a nearly circular cross-section and a perfectly smooth shiny surface. Lower down the surface acquires a dull whitish appearance until finally, at the distance L_2, a slight fraying of the stream begins. This effect is produced by the separation of individual drops at first, followed by constantly increasing numbers, until it seems as though the surface were being peeled off. This peeling continues until the stream is entirely dispersed in drops. After reaching a certain pressure, the smooth shiny surface of the stream just below the nozzle begins to tremble. Rings become evident and, with increasing pressure, appear as constrictions in the stream. The shape of the constrictions is very difficult to recognize at first. From the subsequent course of the phenomenon, we can, however, conclude that these are not contractions of the stream cross-sections in the ordinary acceptation of the term, but that changes occur in the cross-section of the stream which take on the appearance of constrictions. As the pressure is gradually increased, these constrictions seem to proceed in close succession and increasing numbers from the nozzle (Fig. 21B). The constrictions seem to be wound spirally and the portions of the stream between them receive a shape like a bi-convex sickle. There is therefore no bulging of the stream in all directions, but, as in the case of the constrictions,

there are changes in the cross-section of the stream which we will continue to designate by the term "sickles." The sickles just under the nozzle are the shortest, while the ones farther down grow longer and thicker. The middle ones are the longest and thickest. Still farther down, their length diminishes somewhat and their shape is harder to determine. After the last constriction (C), which is scarcely discernable, there is again a closed stream with a smooth shiny surface. As the pressure increases, new constrictions and sickles come from the nozzle and, since the length of the sickles is constantly increasing, their downward velocity also increases. Moreover, the lowest sickles become more visible until their total length l (Fig. 21C) reaches a certain maximum. From this moment on, the lowest sickles begin to disappear and, instead of the hitherto closed cylindrical stream with a smooth surface, a sharply pointed cone, with a dull surface and occasional slight fraying, begins to emerge. From this point on, l again begins to shorten, since the constrictions disappear more rapidly at the bottom than the sickles can form at the top. Therefore, the number of the sickles diminishes rapidly, becoming continually longer and broader and, below the last constriction, the transition into a pointed atomization cone or jet grows constantly more apparent (Fig. 21D). From D, by the bursting open of the third constriction, the jet E is obtained and, by the further opening of the second constric-

tion, the jet F. The fewer sickles there remain and the larger they are, just so much better their shape can be observed. It was found that the sickles consist of a thin sheet of oil with many longitudinal folds (Fig. 22). The cross-section AB is nearly rectilinear or slightly and irregularly bent. At the constrictions, the jet seems to rotate about 180° and the particles of oil seem to cross over. Thereby, the spiral motion, imparted to the jet by the atomizer rods, does not seem to determine exclusively the direction of rotation of the jet, since it often changes its direction arbitrarily when the pressure changes. The oil sheet continues a little beyond the last constriction. It seems as though it were trying to draw together again so as to form a new constriction, but lacks power to do so and splits up into quite large drops. This phenomenon is especially characteristic after the opening of the last constriction (Fig. 21G). The oil sheet (whose length is L) draws together so strongly at first that the outer edges of the jet are almost parallel. If the pressure is increased a little more, the oil sheet becomes shorter, atomization begins sooner and the edges of the jet spread farther apart. Thereby the oil sheet, corresponding, after being split up, to the atomized portion of the jet adjoining it below, has a nearly flat cross-section, so that it gives the jet a fan-shape (H). So long as it is completely closed, the oil sheet has a smooth shiny surface. Then it

forms a narrow zone of dull whitish appearance and the atomization begins. The point where the oil sheet splits up into drops cannot be determined with absolute accuracy. If a needle is held in the jet, even in the region where atomization has already begun, drops are immediately thrown off by the needle. If, on the other hand, the needle is introduced into the oil sheet, the oil sheet first spreads just a wee bit on the needle and then breaks up and throws off drops. It is especially noticeable that the introduction of the needle, aside from the disturbance at the point of immediate contact, causes no change in the jet. While the jet shows itself so stable toward external attacks, it is all the more sensitive to any variation in its internal forces. The finest dust particles which get into the nozzle along with the oil, cause a constantly changing appearance of the jet. The drops, which fly off the needle, appear to be coarser (instead of finer) than the drops in the real atomizer jet.

When the pressure is further increased, the nozzle begins to whistle. The fuel jet grows more irregular, the upper portion of the oil sheet begins to fold together or to curl up like a wilted leaf and changes from the fan-shape H to the cone-shape J. As soon as this transition is completed, the jet becomes more regular and the whistling decreases. The drops are temporarily still quite large in this cone. The atomization becomes finer and more uniform only after a fur-

ther pressure increase, in which the oil sheet continues to grow shorter. Finally the oil sheet grows very short and almost vanishes and the jet assumes a regular cone-shape K, with a slightly rounded apex, the whistling having entirely ceased. The atomization appears fine and uniform and a fine oil cloud begins to hover about the apex of the cone. The jet has assumed its final form, which undergoes no particular change when the pressure is further increased. From this moment on, our experiments first acquired their full validity, since previously the oil sheet was cut by the shutter, thereby somewhat affecting the formation of the drops.

The above description holds good in principle, for both gas oil and kerosene and for the nozzle with either of the atomizer rods or without any. By laying the hand on the pressure piston, it is possible slightly to increase or decrease the pressure and cause the jet to pass forward and backward through the various changes, thereby demonstrating that the various forms of the jet always correspond exactly to the pressure. By comparing the effect of the liquid and of the spiral groove on the process, it is found that with a larger groove, a somewhat lower pressure is required in order to produce similar effects with the same liquid. Here the "sickles" are much more pronounced and the constrictions nearer together. When there is no spiral groove,* similar phenomena

* A slight spiral motion is almost always present, even in smooth-bored tubes, or it may be produced by some slight obstacle. The reference here is to the absence of any atomizer rod.

still appear, but they are much less pronounced and their course is considerably retarded, i.e., their production requires a much higher pressure and the constrictions are farther apart. The transitions follow in more rapid succession with kerosene than with gas oil. The latter liquid requires twice as much pressure as the former, in order to produce the same phenomena with the same spiral groove. With gas oil, the constrictions are two or three times as far apart and the sickles are less pronounced. The maximum number of sickles is smaller for gas oil than for kerosene. When gas oil is employed without the spiral groove, the jet forms are much retarded and more than three times as much pressure is required as for producing similar phenomena with kerosene, but this difference between the two liquids is greatly diminished in the subsequent jet forms, which occur at higher pressures. Here the distance between the constrictions seems to be about the same for the same number of sickles. In general, we may say that the characteristic forms of the jets are the more pronounced and the lengths of their separate parts, especially the distances between the constrictions, so much the shorter, the smaller the pressure required to produce these forms. On the other hand, less pressure is required to produce similar jet forms, the thinner the liquid and the stronger the rotary motion.

The strength of the rotary motion is expressed in the

size of the angle at the apex of the jet. This was measured with a special instrument (Kuehn, previous reference, tables on p. 175) and is plotted against the pressure in Fig. 23. It is shown that, as soon as the atomization cone is fully developed, no further increase in the pressure can change the apex angle. If the grooves in the atomizer rods are made less steep, the apex angle of the cone does not increase in exactly the same ratio. This may be due to the fact that the nozzle bore is long in comparison with its diameter and that therefore the radial component of the spiral motion in the long groove is partially destroyed by friction. The length of the groove and especially the angle at which the fuel enters the groove from the preceding space is certainly of decisive importance for the determination of the cone angle, since the latter can be considerably increased by using nozzles which differ from the ones employed by us. Unfortunately we could not undertake experiments in this direction, because there were no other nozzles available for our use. The fact that the fully developed atomization cone leaves the nozzle with a very short bulge (Fig. 21K) seems to indicate that, immediately under the orifice, capillary forces tend to draw the jet together before atomization begins. If the sides of the cone are prolonged to their point of intersection, it is found that the apex of the cone penetrates quite deeply into the nozzle orifice. At the high pressures, probably no contraction of the jet occurs inside the nozzle.

For comparison with gas oil and kerosene, experiments were also undertaken with lubricating oil. It was found that the outflow of the latter was very slow and irregular. After the nozzle cock was opened, the discharge began with considerable hesitation and, after the cock was closed, there was a longer after-flow or dripping. The rate of flow at constant pressure varied greatly and, even at higher pressures, diminished very noticeably in a short time. For this reason, further discharge measurements with lubricating oil were abandoned. The jet was fully closed, of circular cross-section and had a shiny surface. No atomization of it could be effected. At the maximum pressure (about 42 kg/cm^2) obtainable with our experimental equipment, the smooth closed jet first began to show barely noticeable constrictions. It is therefore probable that no true vaporization cone could be produced at pressures of less than 80 kg/cm^2.

Experiments were also undertaken for studying the behavior of a vaporization jet in a narrow enclosed space. For this purpose we employed a glass balloon having a spherical portion 225 mm in diameter and a neck 225 mm long with a diameter of 45 mm. The glass sphere also had two diametrically opposite openings of 25 mm diameter. The nozzle was introduced, through a perforated cock, into one of these three openings. Gas oil was then vaporized in the balloon and an attempt was made to establish the occurrence of refraction phe-

nomena. These experiments failed completely, in spite of the fact that the balloon was densely filled with oil drops and, especially, that the fine oil cloud which surrounds the atomization cone at high pressures, could not escape laterally, because the size of the drops varied too much for the formation of an aureole around the observed source of light. Moreover, immediately after the injection, the inside of the balloon becomes covered with an oil film which, on the curved walls, strongly reflects the light and soon becomes so dense as to completely lose its transparency. When the fuel is injected into the balloon, the larger drops strike the walls and flow together, while the fine oil clouds are carried away from the vaporization cone by air eddies and hover throughout the balloon. When the fuel, instead of being introduced through one of the small openings directly into the spherical portion of the balloon, is injected into the neck, the oil clouds are less extensive. This is due to the fact that only a portion of the finer drops pass through the long neck into the spherical part of the balloon, while some of them are brushed aside by the larger drops and adhere to the inside of the neck. If the fuel is injected through one of the small openings and a reflecting surface is introduced through the opposite opening, there is formed on the inside wall of the balloon a broad oil ring, which lies in about the same plane as the reflecting surface and changes position with the latter.

This ring is produced by the combining of very large drops thrown off from the reflecting surface. On the reflecting surface there is formed a thin oil film which flows toward the edge, from which it is blown off in very large drops in the direction of its plane. Most of the drops which strike this liquid film are carried away by it instead of being reflected at their angle of incidence. The atomization is therefore not improved by the reflecting surface since the reflected drops are enlarged by combination with other drops and the rest combine with the oil film on the reflecting surface, their direction of motion being principally deflected into the plane of the reflecting surface. A diminution of the fine oil cloud is also noticeable after the introduction of the reflecting surface.

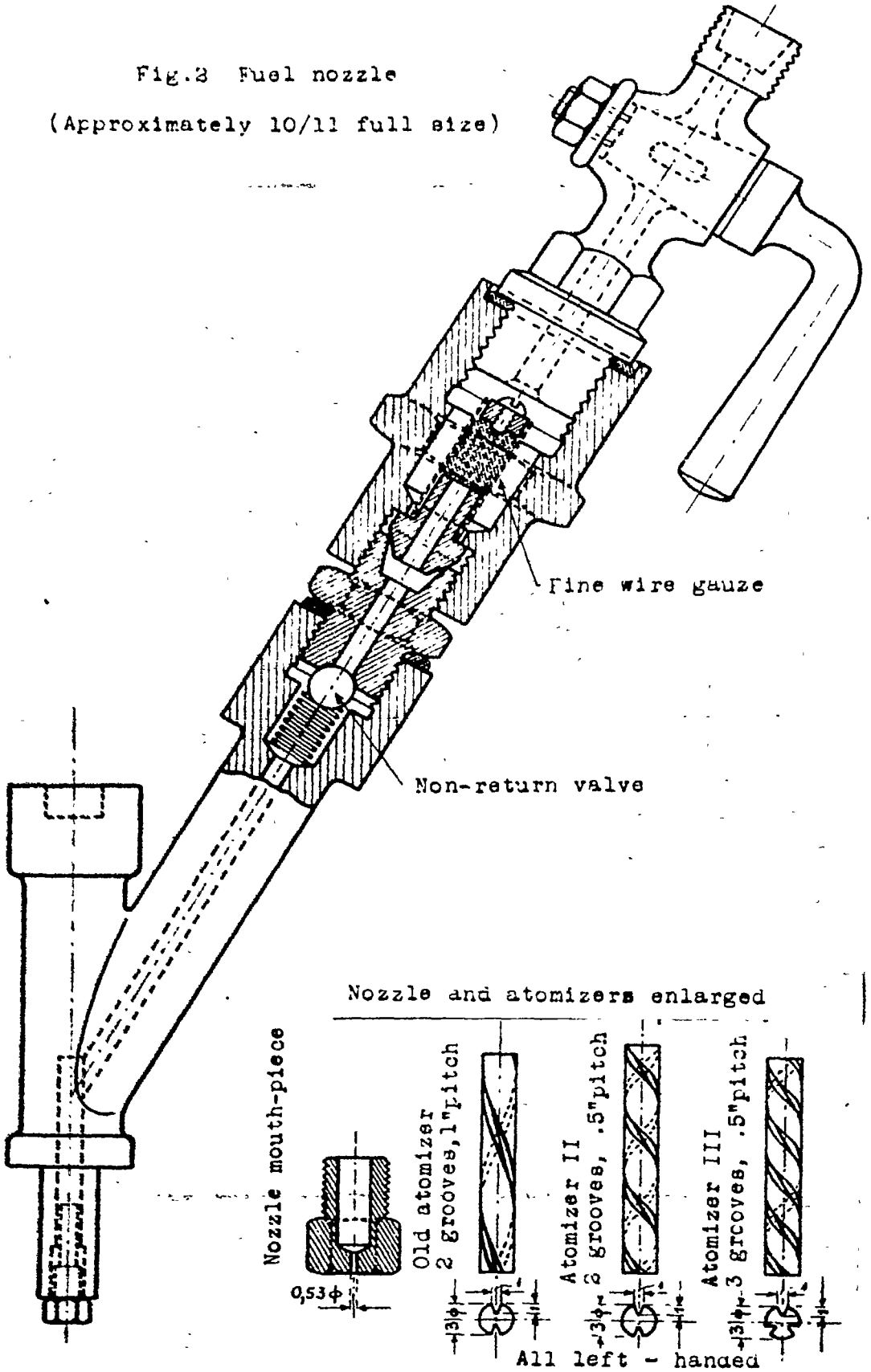
The following experiment was also tried with the glass balloon. It was entirely filled with water and the fuel was then injected. The jet formation was retarded so much by the greater density of the water as to render it possible to observe how the jet emerged from the nozzle after the cock was opened. A sausage-shaped cloud formed in front of the jet. This cloud grew rapidly, was driven against the opposite wall by the conical jet and finally filled the whole balloon. It was observed that an eddying motion was gradually imparted to all the water by the closed jet, which was still quite dense near the nozzle, and that the water eddies carried along

the oil drops and distributed them throughout the entire space. As soon as the eddies had completely filled the balloon with oil drops, it was impossible to see through the balloon and consequently no more experiments were tried in this direction, since they did not promise to shed any light on the nature of the fuel jet.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

Fig.2 Fuel nozzle

(Approximately 10/11 full size)



A, Motor 1/6 HP. 2000 R.P.M.
B, " 3/4 " 1850 "
C, Thermometer. D, Cock 1 ϕ5mm
E, Length 1150 1 ϕ 3.5 mm
F, Strainer and non-return valve
G, Nozzle. H, Shutter. I, Cock 1 ϕ 4mm
J, Length 520 1 ϕ 4 mm. K, Length 780 1ϕ 10 mm
L, Drain pipes. M, Thermometer. N, Pad.
O, Fuel tank 500 x 370 x 270
P, Wire strainer. Q, 1 ϕ 10 mm.
R, Pump piston,bore 12 mm, stroke 16.5 mm.
S, Large pressure piston, 20 ϕ
Small " " 10 ϕ
T, Overflow. U, Weights.
V, Pressure gage. W, Cock 1 ϕ 9 mm.
X, Air chamber, 12 liters.

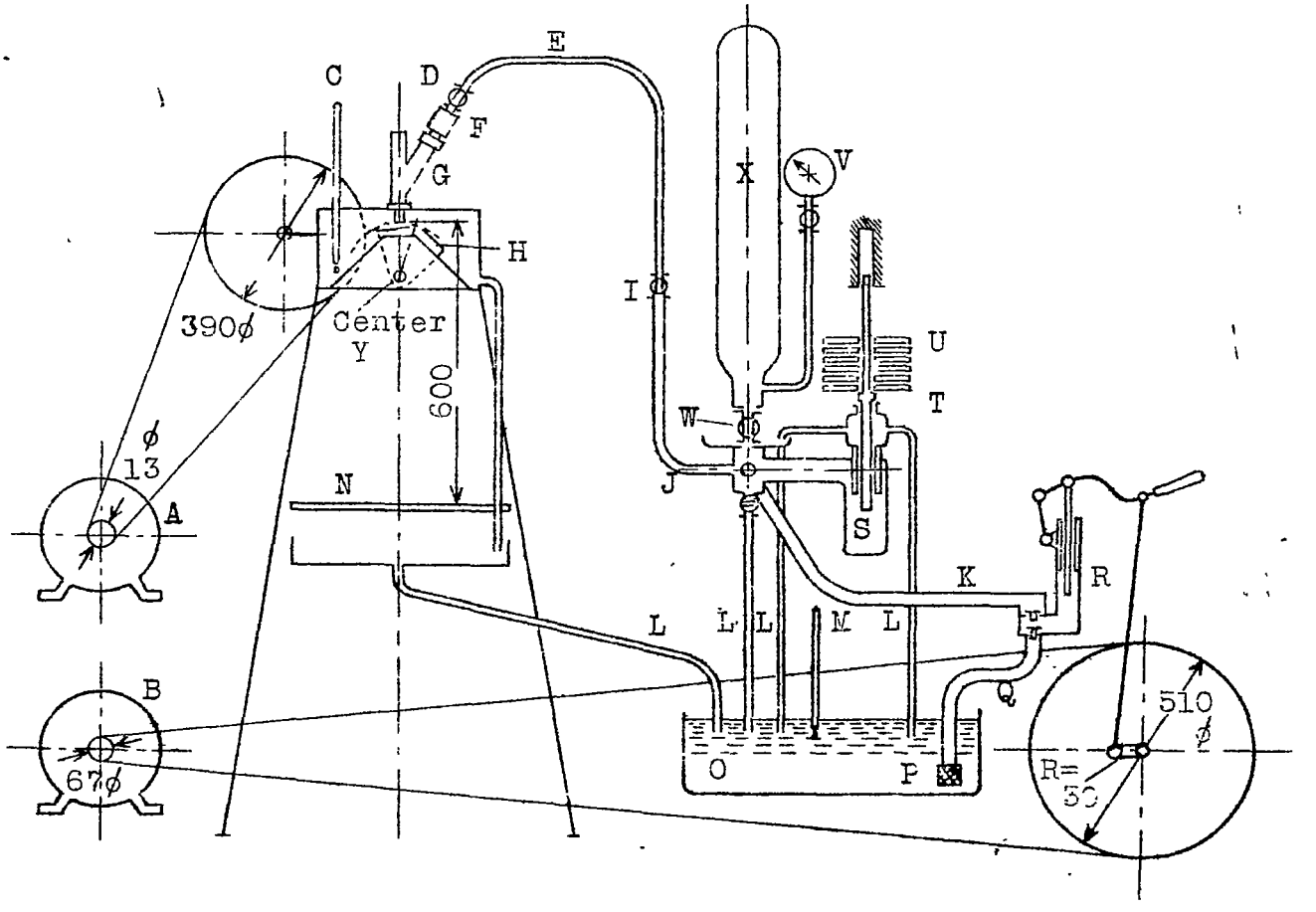


Fig. 3 Diagram of arrangement of apparatus

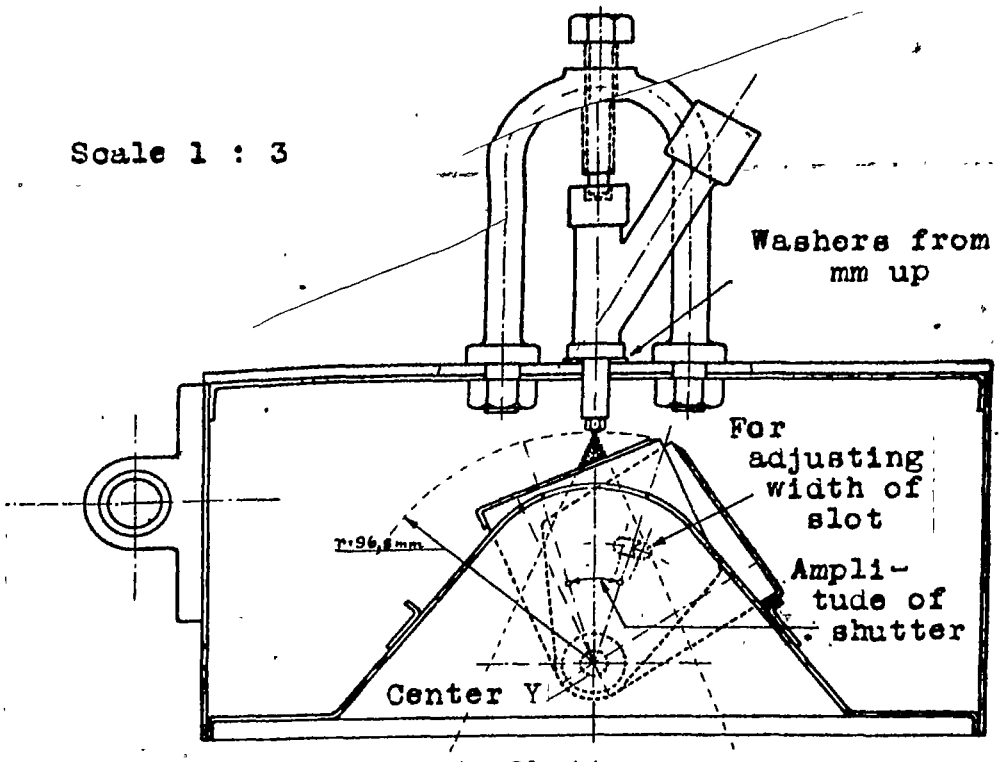


Fig. 4 Shutter

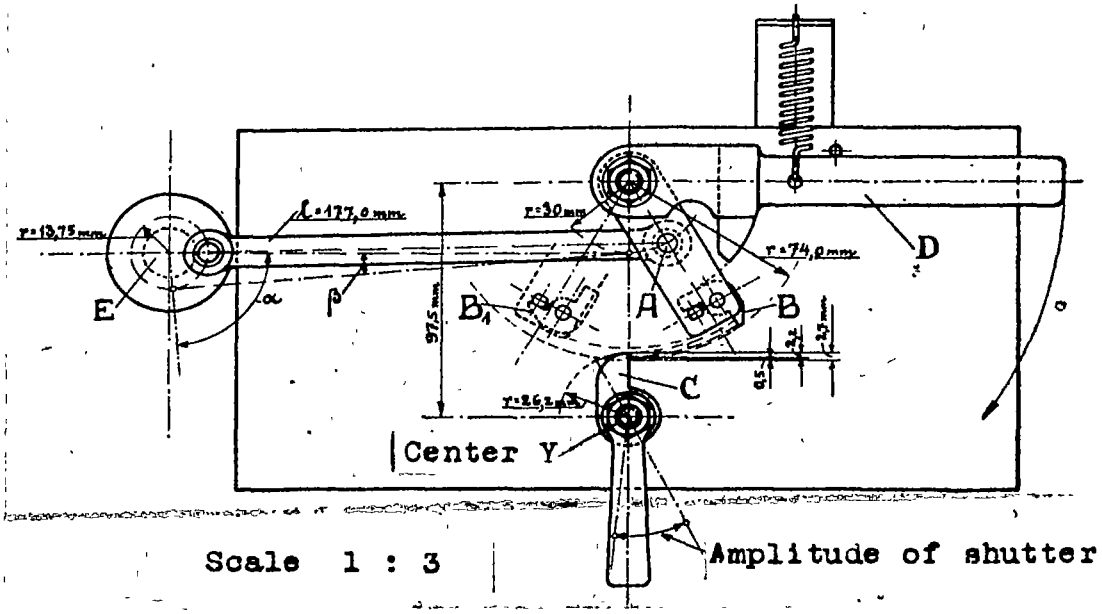
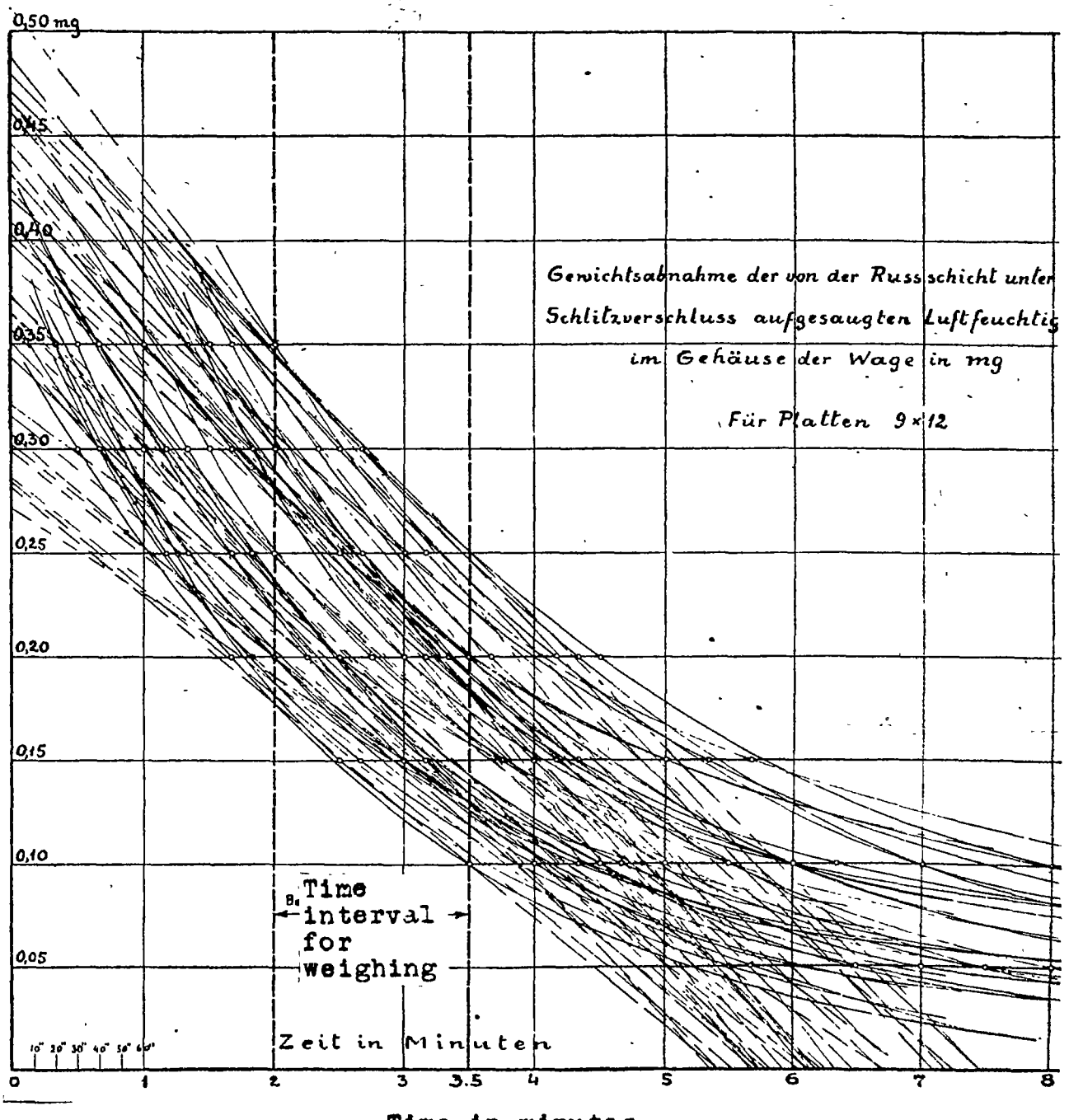


Fig. 5 Shutter drive



Time in minutes

Fig. 6 Loss in weight (in mg), in the balance case, of the atmospheric moisture absorbed by the soot layer while under the shutter.

For plates 9 by 12 cm

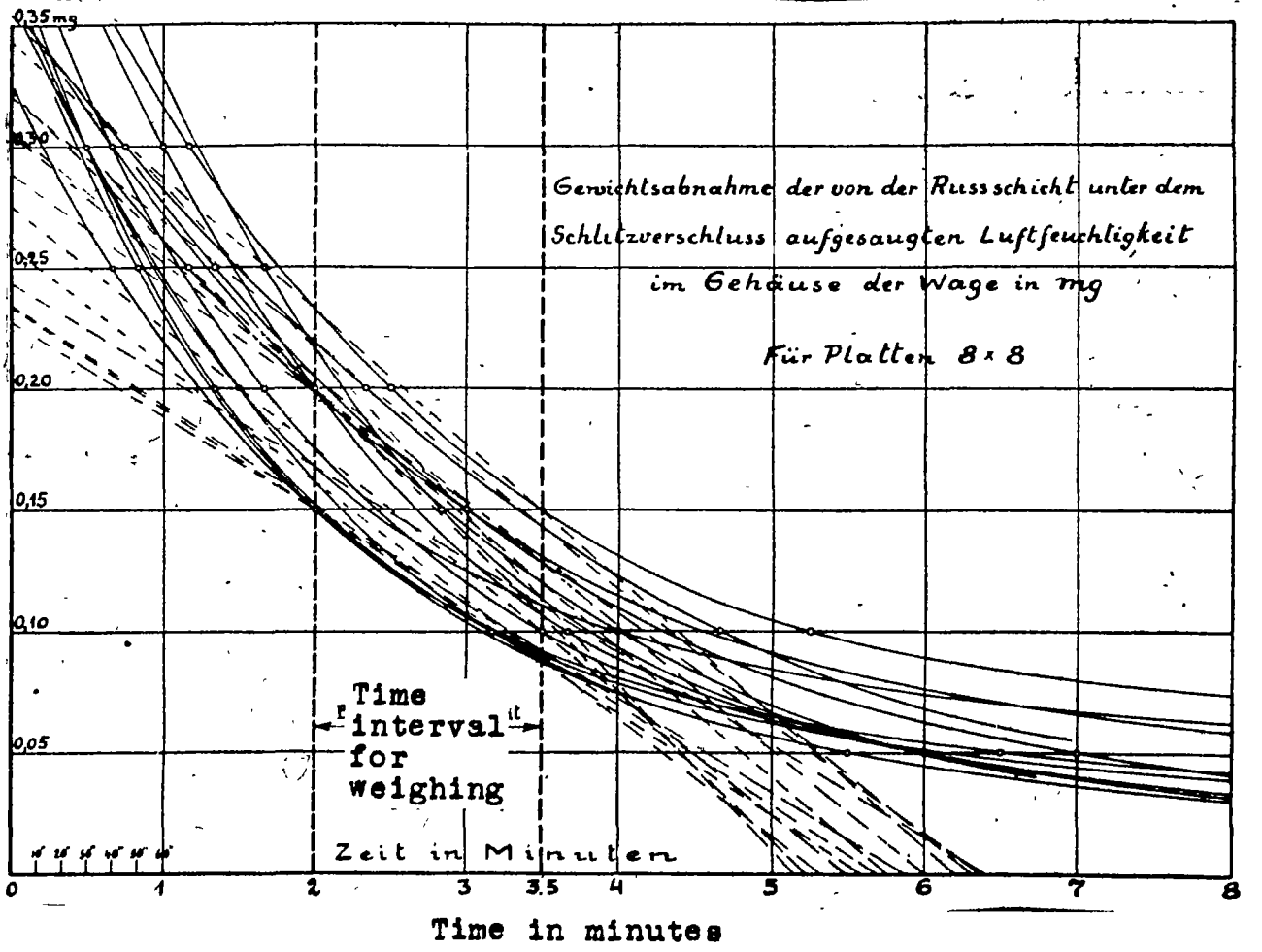


Fig. 7 Loss in weight (in mg), in the balance case, of the atmospheric moisture absorbed by the soot layer while under the shutter.

For plates 8 by 8 cm.

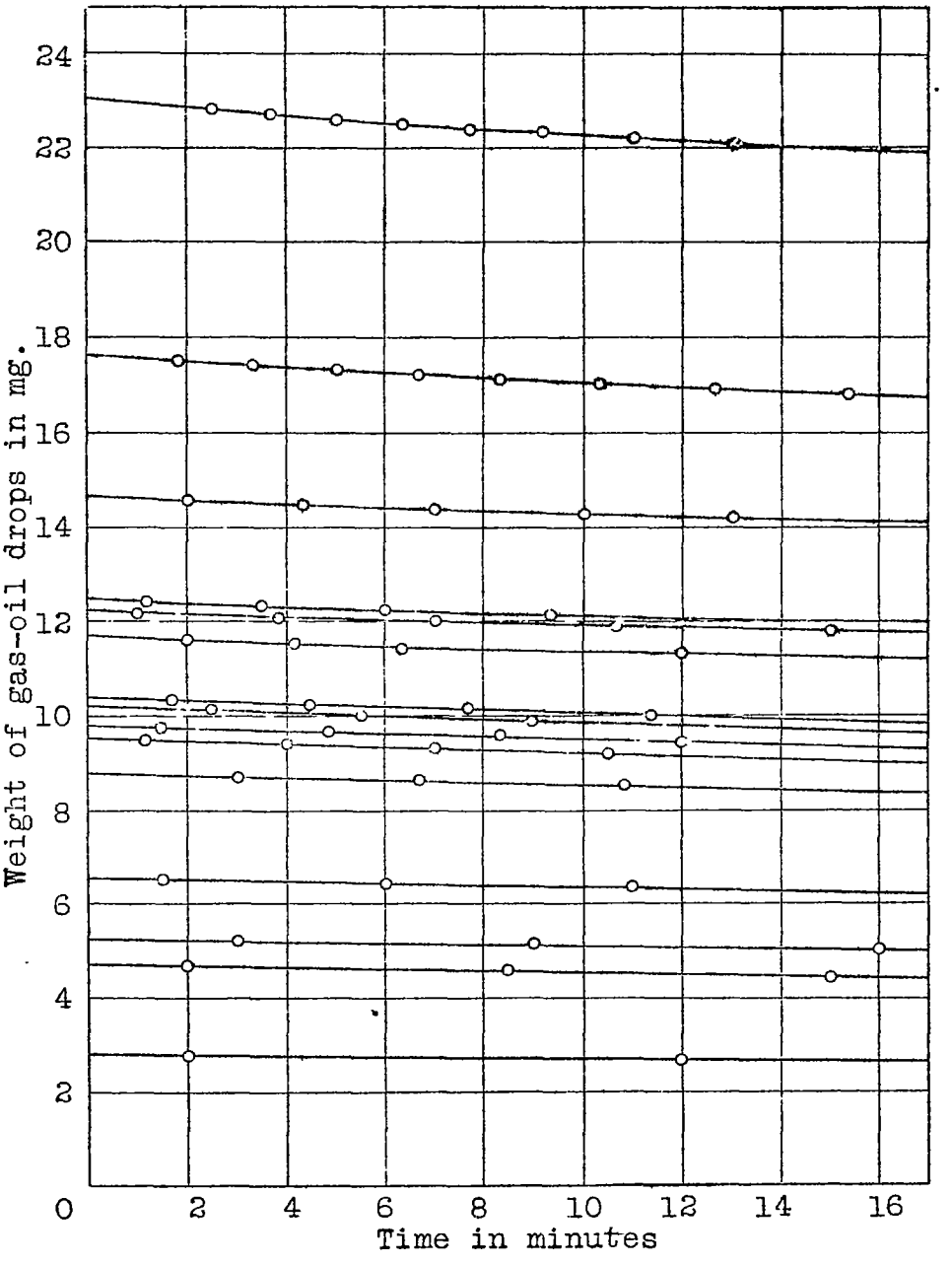


Fig.8 Evaporation of gas-oil drops from smoked-glass plates

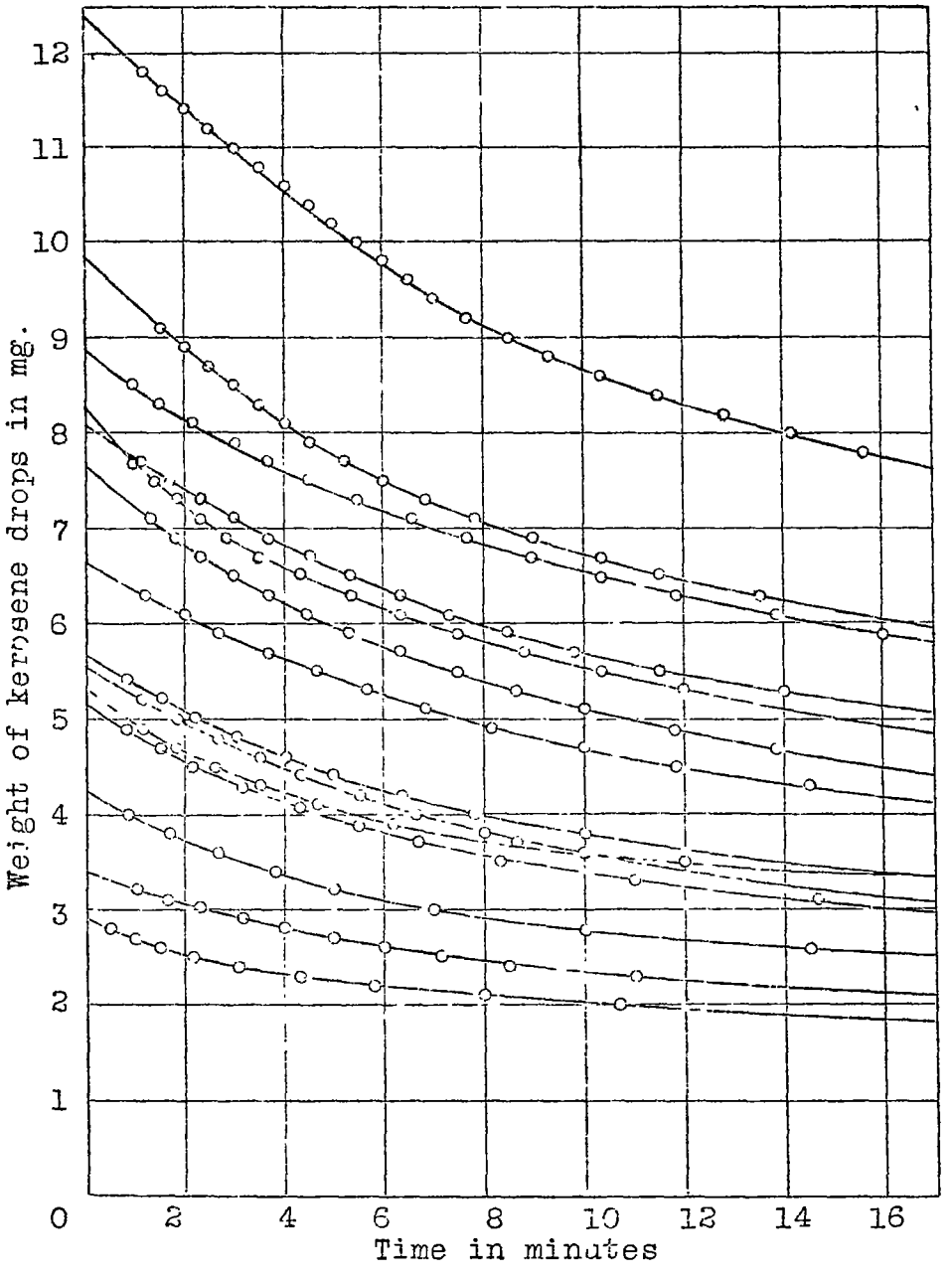


Fig.9 Evaporation of kerosene drops from smoked-glass plates

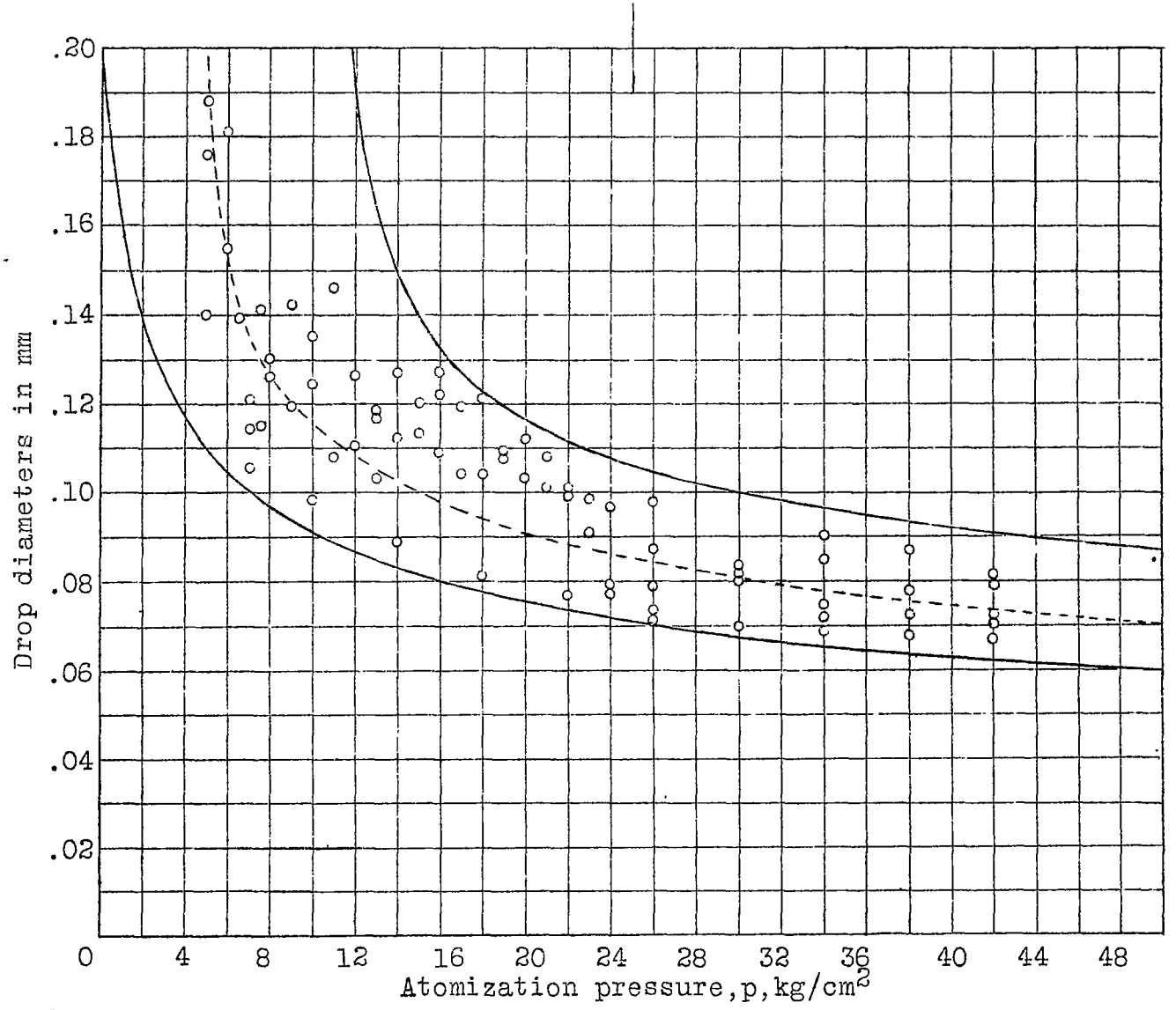


Fig.10 Experiments with gas-oil. Size of drops. Nozzle with old atomizer.

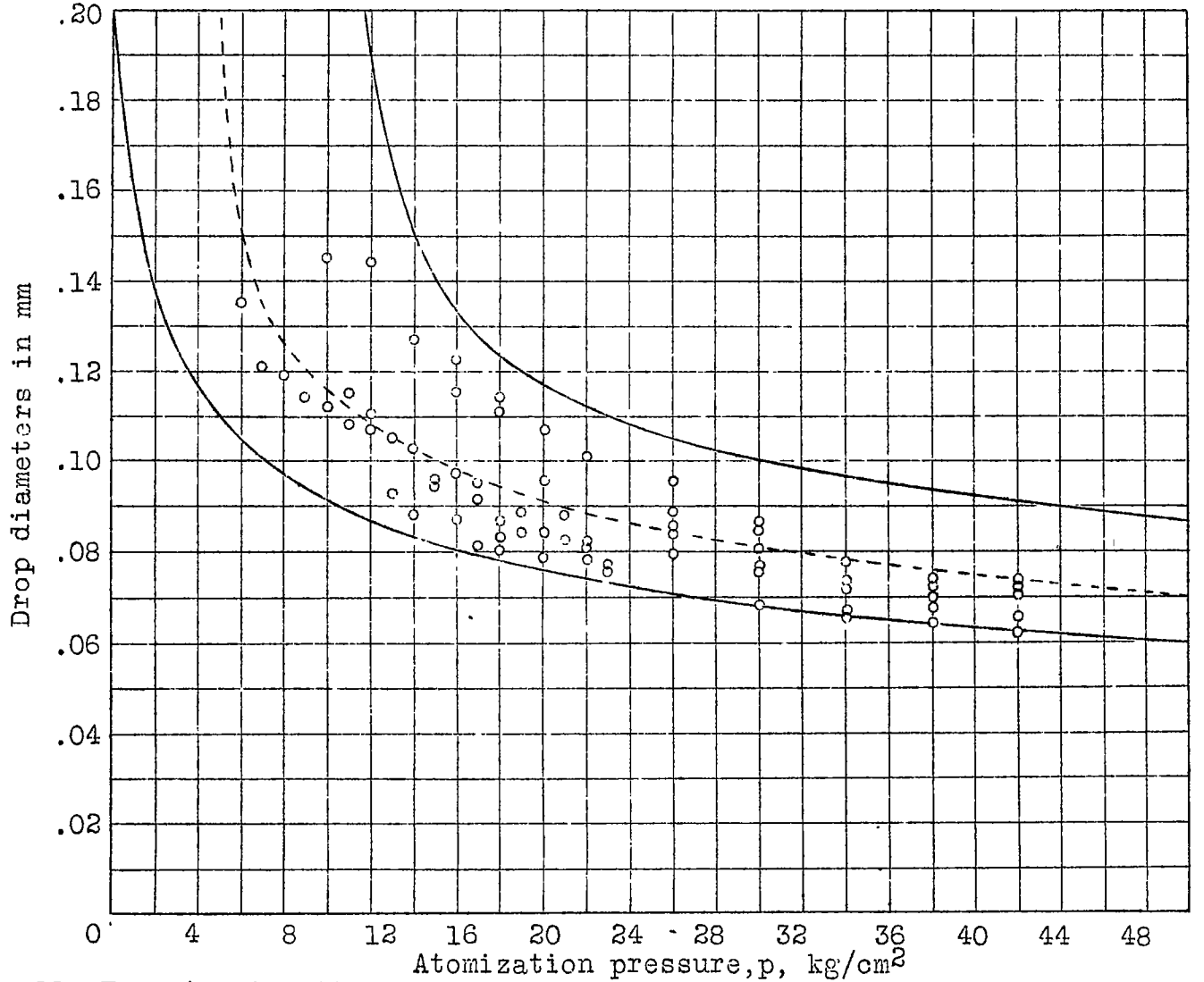


Fig.11 Experiments with gas-oil. Size of drops. Nozzle without atomizer.

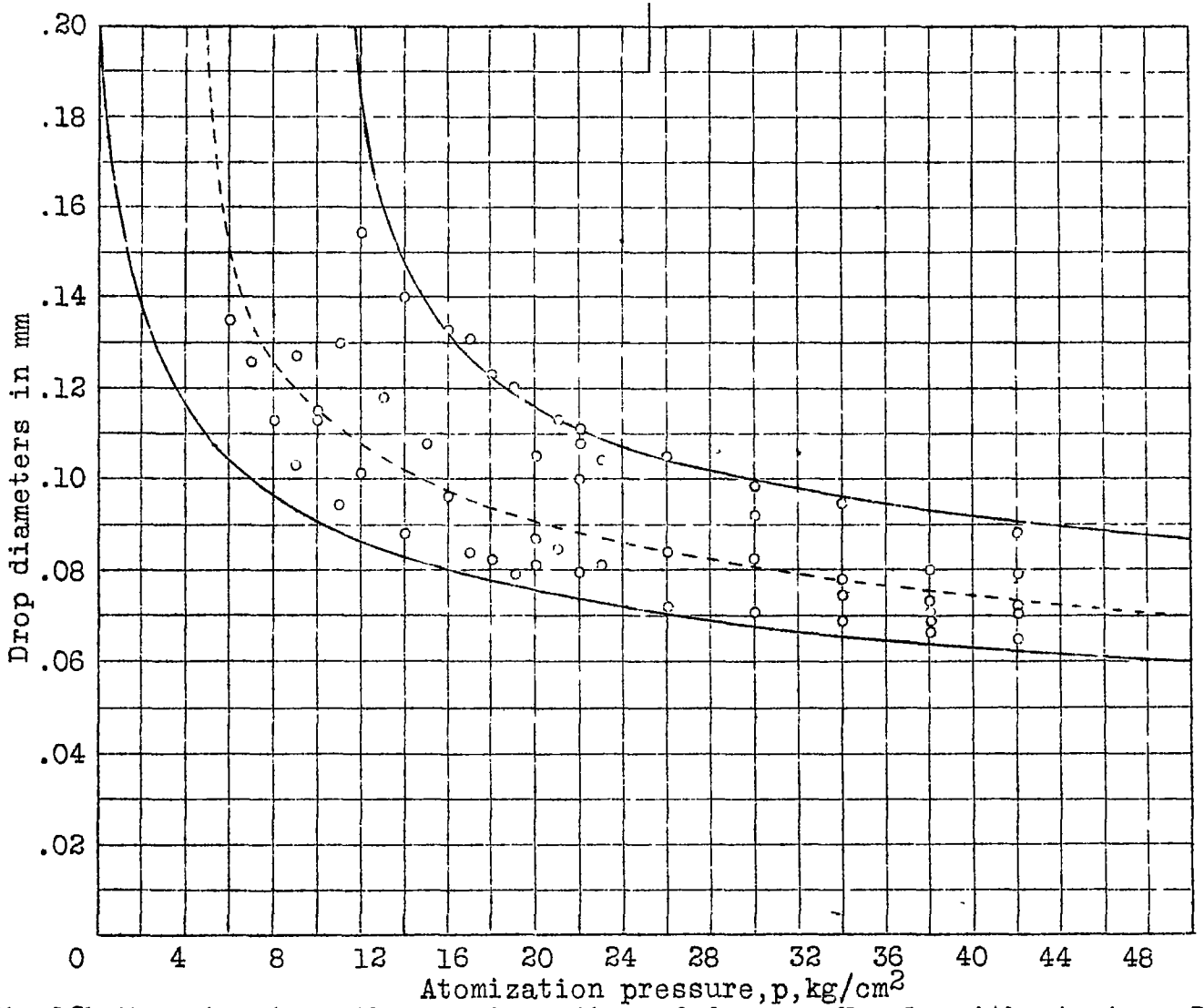


Fig.12 Experiments with gas-oil. Size of drops. Nozzle with atomizer II

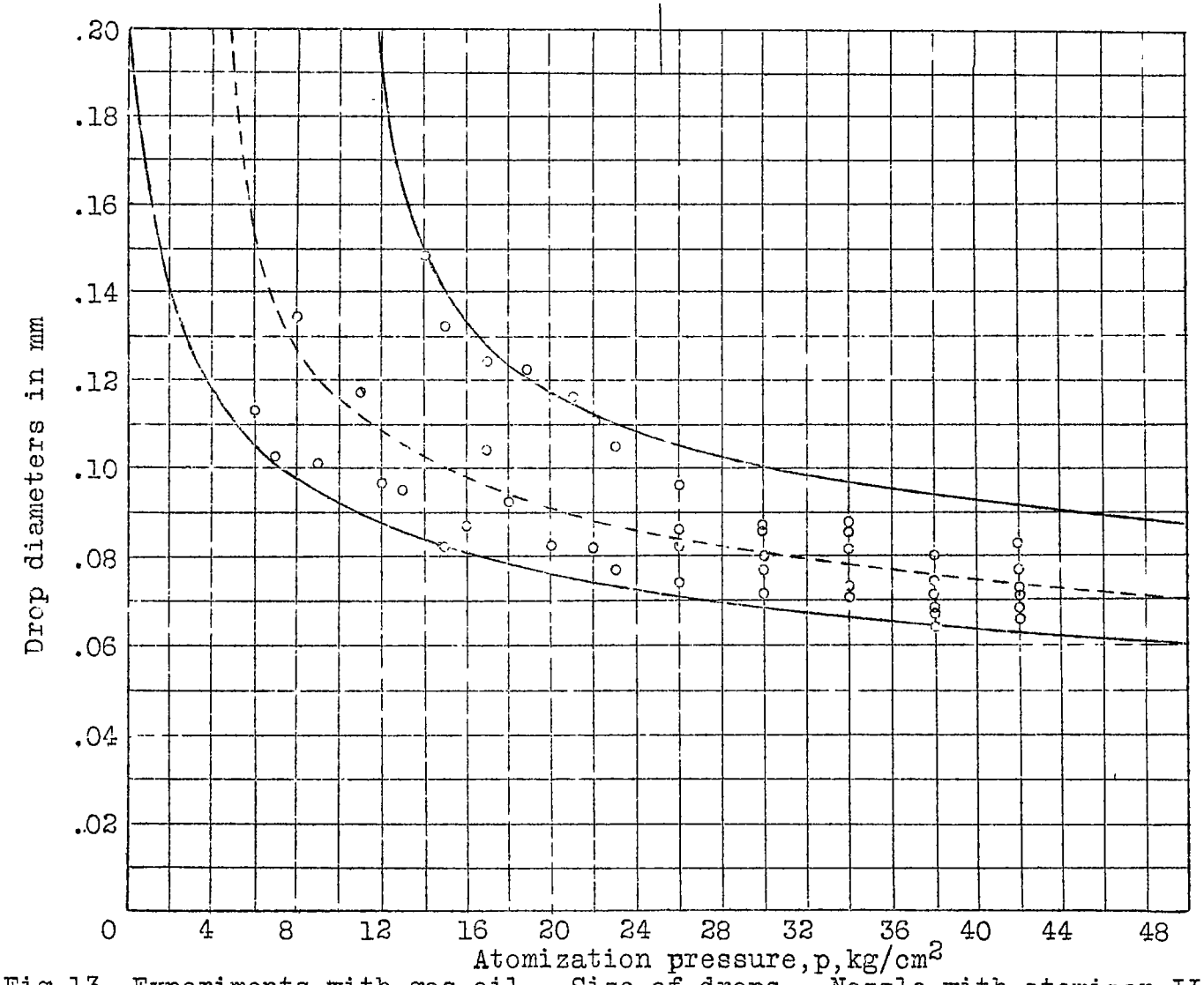


Fig.13 Experiments with gas-oil. Size of drops. Nozzle with atomizer III

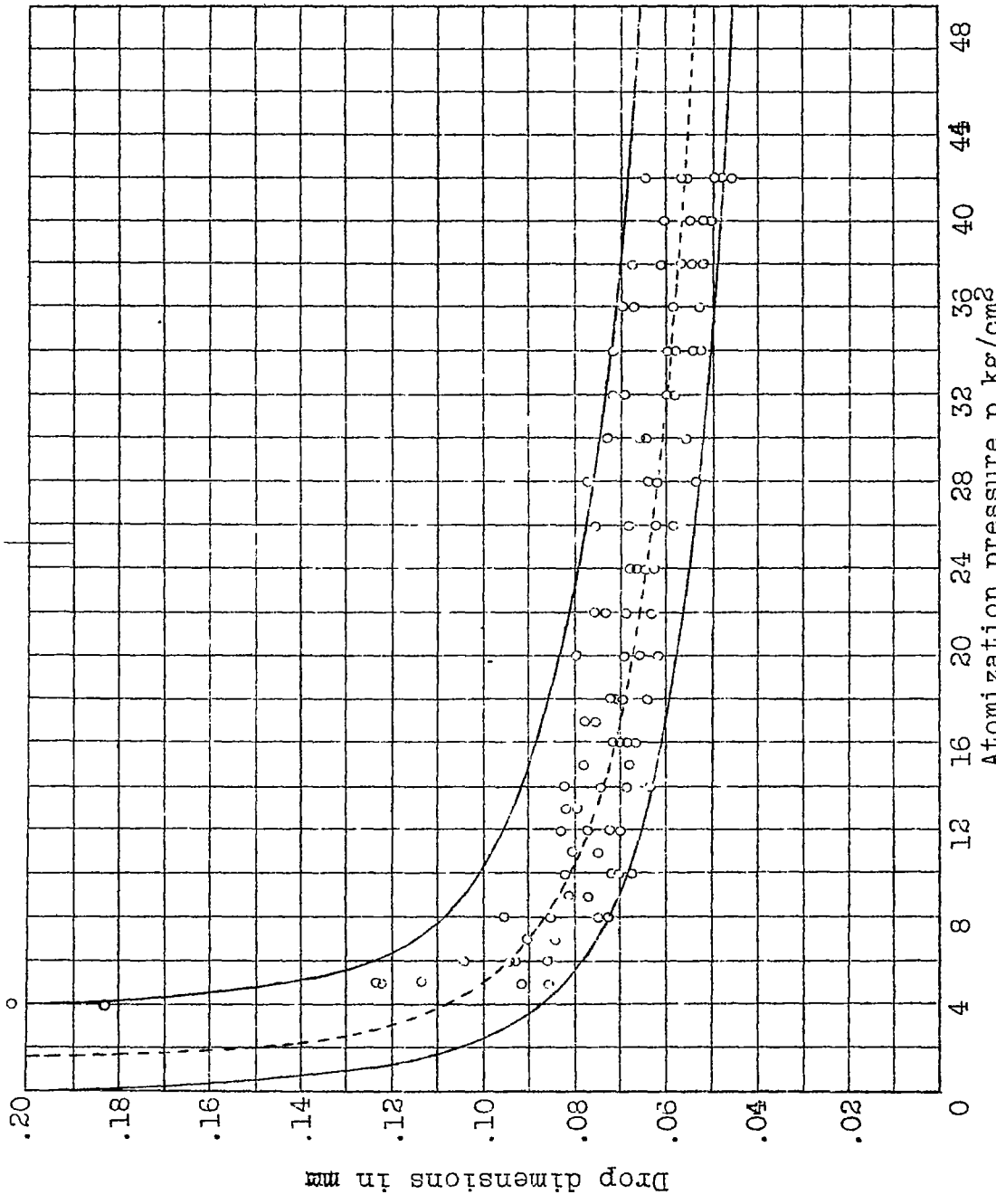


Fig.14 Experiments with kerosene. Size of drops. Nozzle with old atomizer

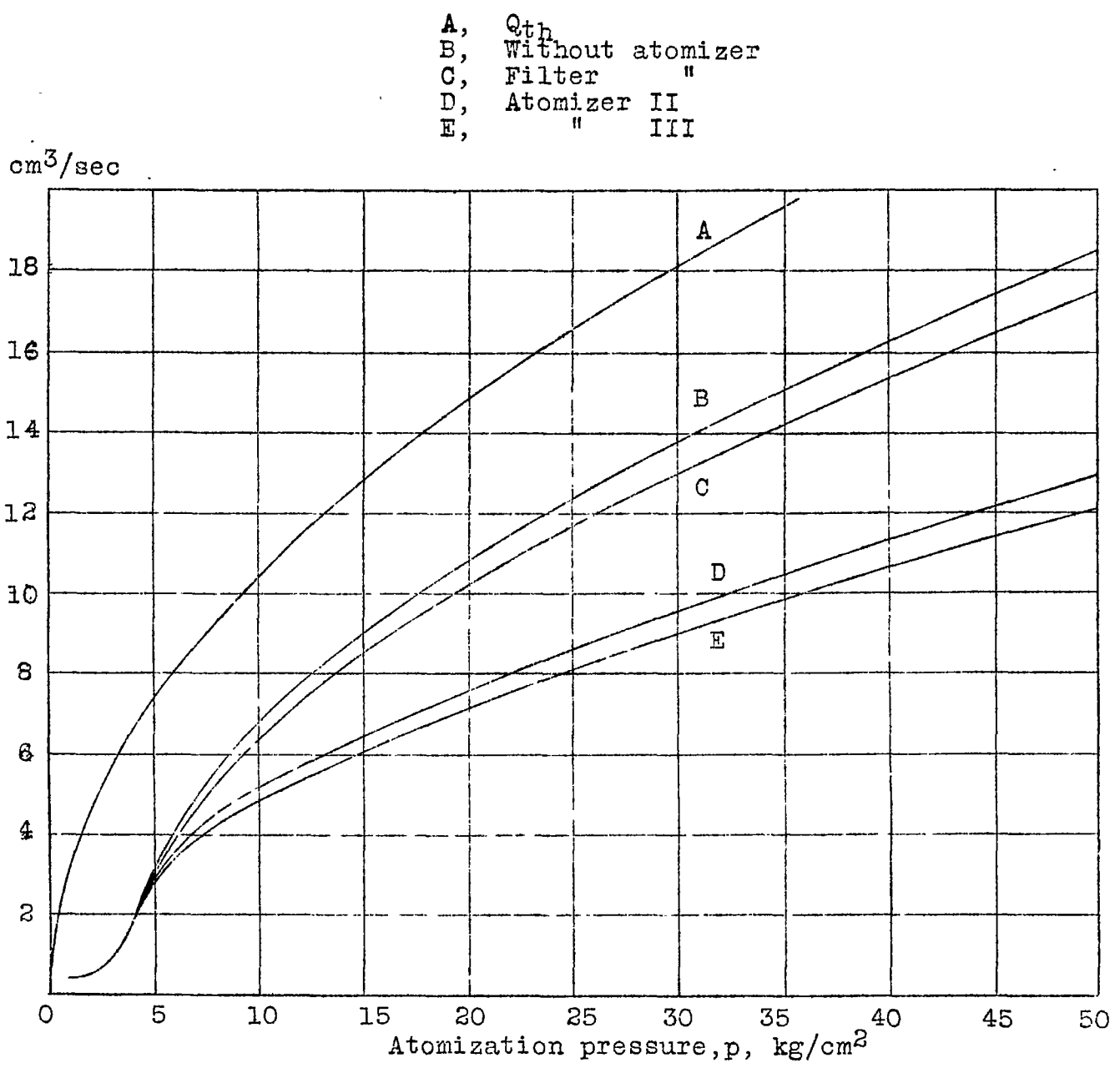


Fig. 15 Experiments with gas-oil discharge quantities in cm^3/sec

A, Q_{th}
B, Without atomizer
C, Old "
D, Atomizer II
E, " III

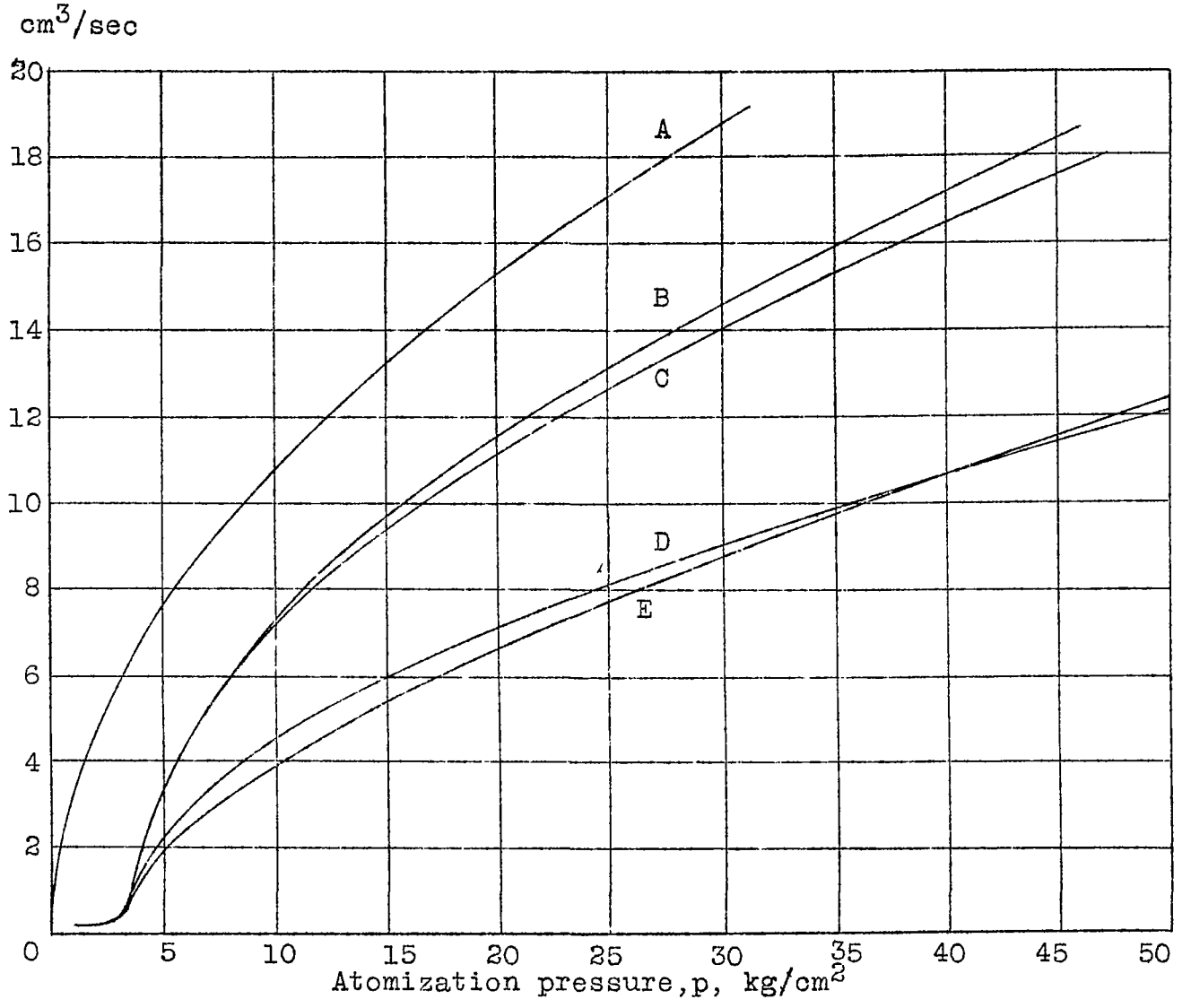


Fig.16 Experiments with kerosene discharge quantities, Q in cm^3/sec.

A, Without atomizer
E, Old "
C, Atomizer II
D, " III

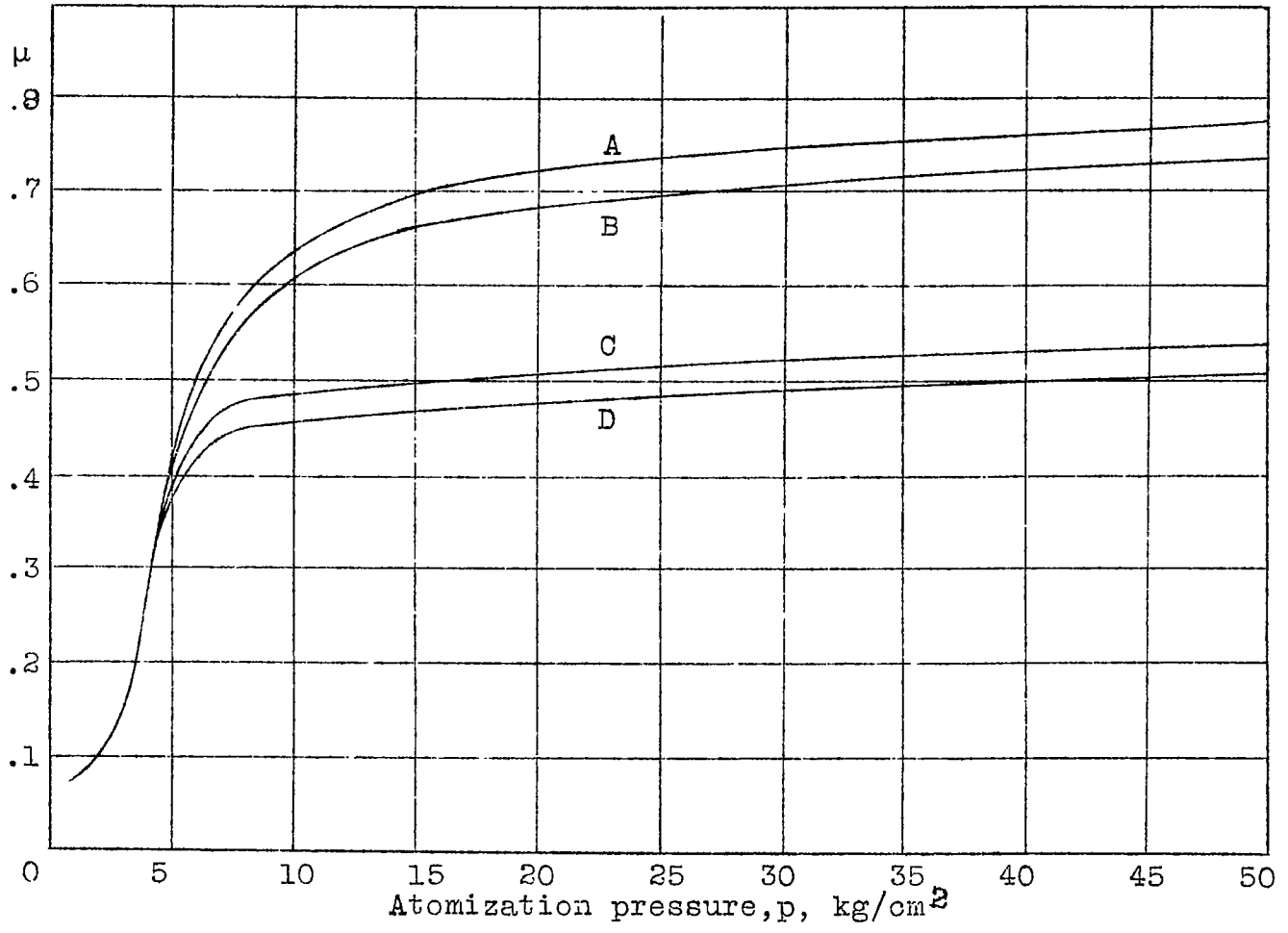


Fig.17 Experiments with gas-oil discharge coefficient μ

B, Without atomizer
C, Old "
D, Atomizer II
E, " III

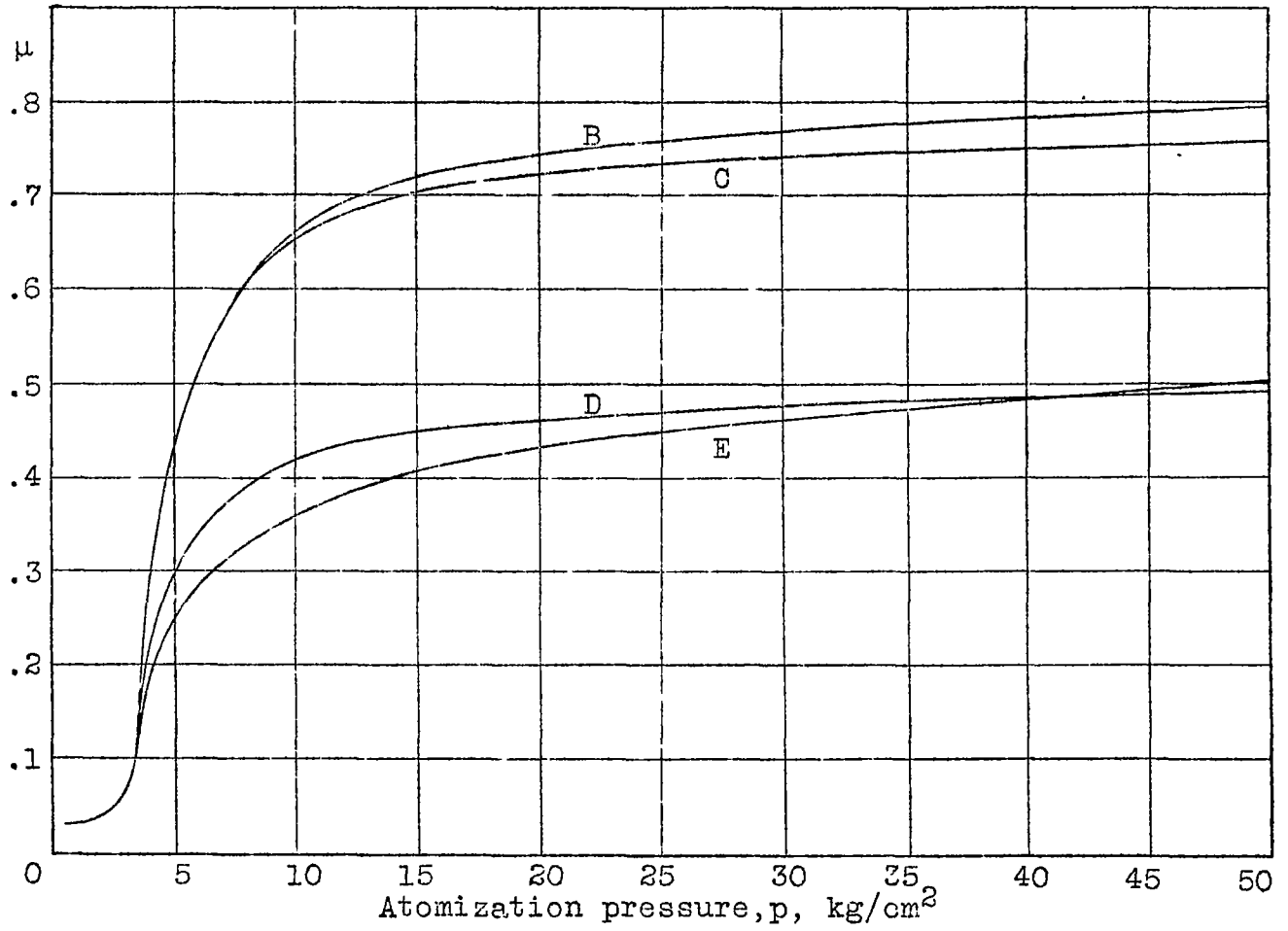


Fig.18 Experiments with kerosene discharge coefficient μ

A, With
B, Without atomizer
C, Old "
D, Atomizer II
E, " III

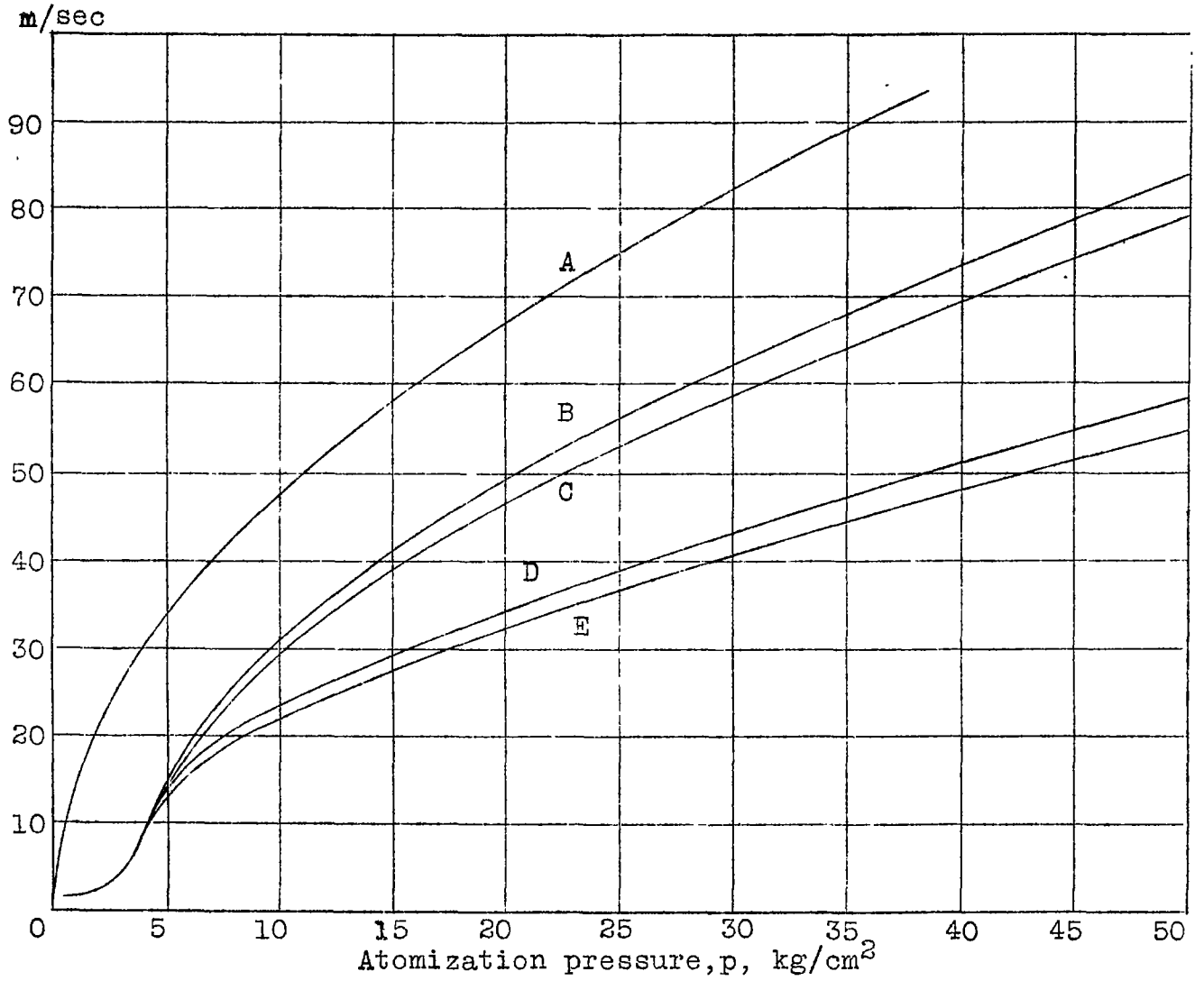


Fig.19 Experiments with gas-oil discharge velocity,w in m/sec

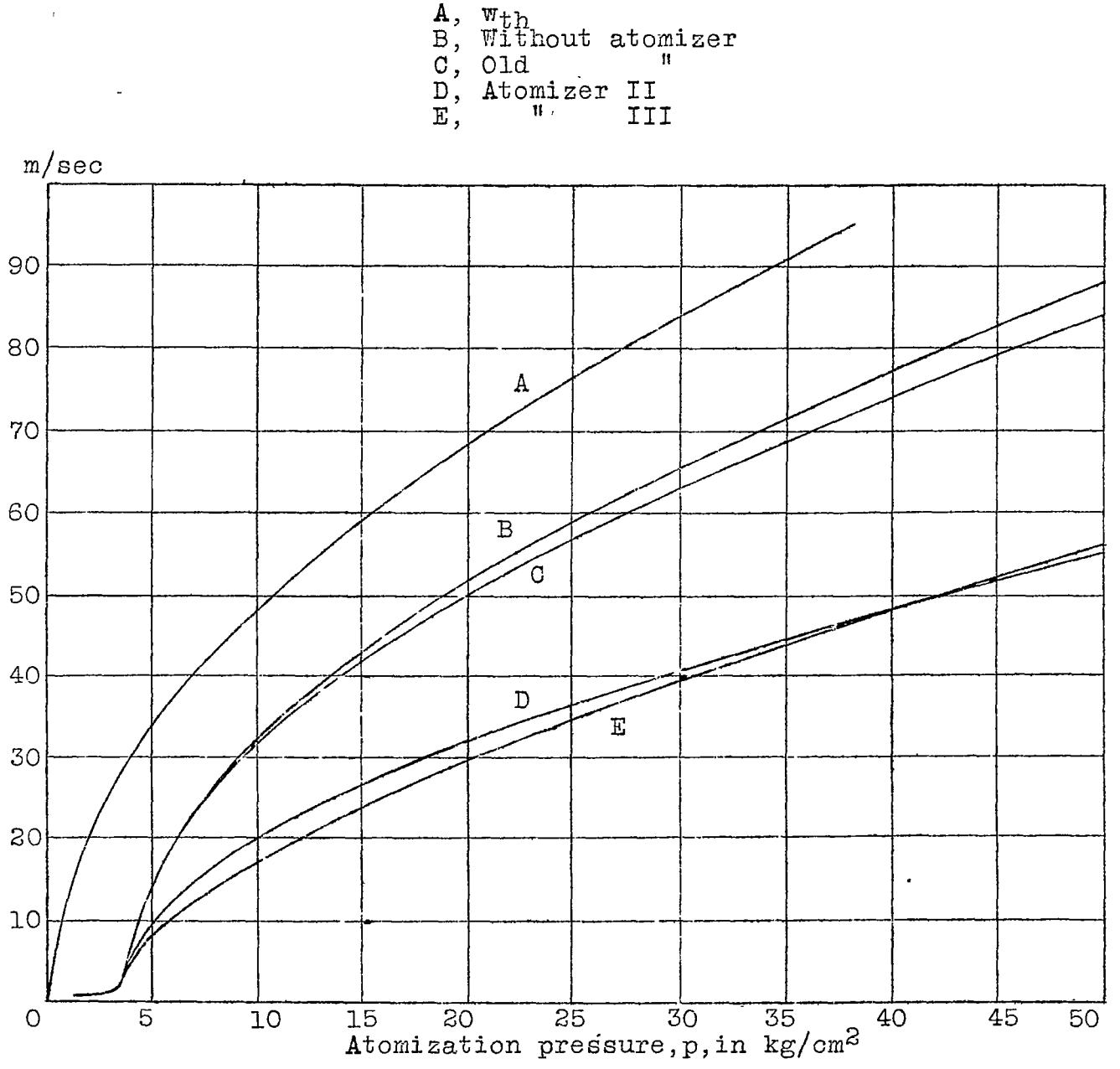


Fig.20 Experiments with kerosene discharge velocity, w in m/sec

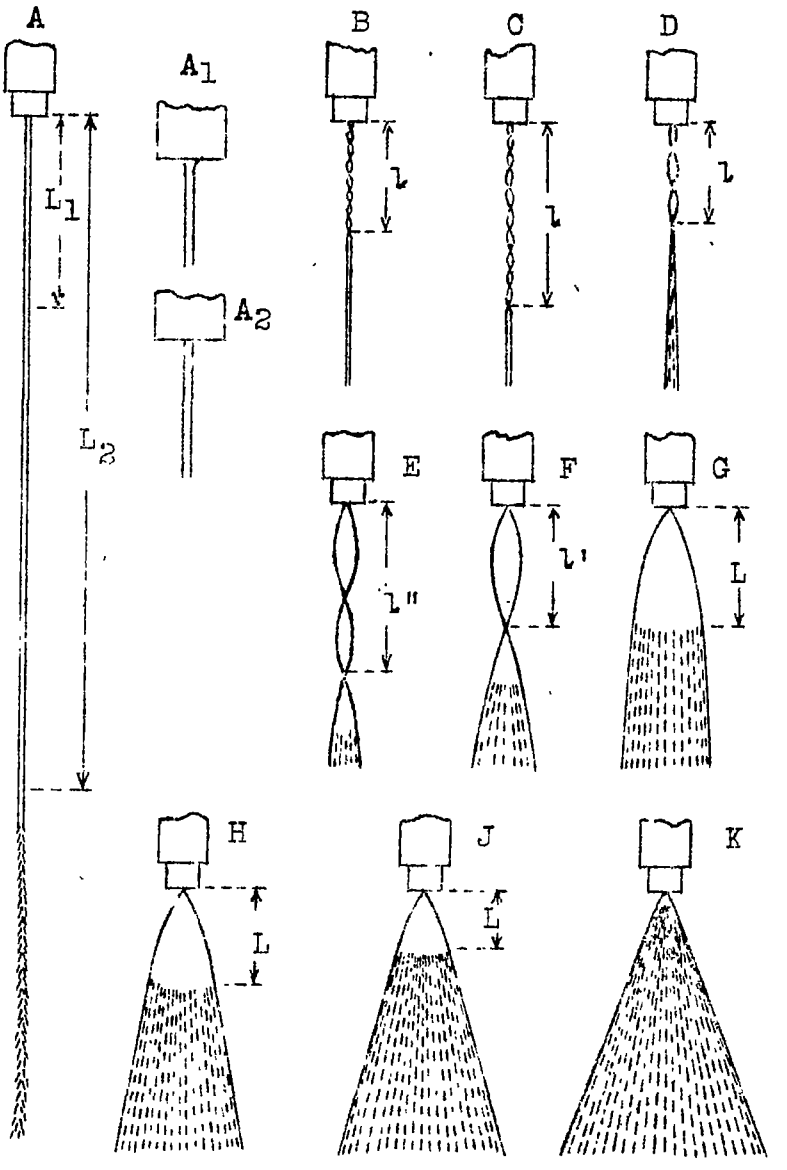
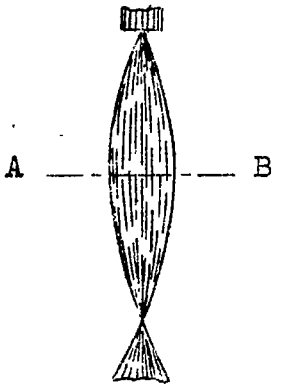


Fig. 21



Cut AB

Fig.22

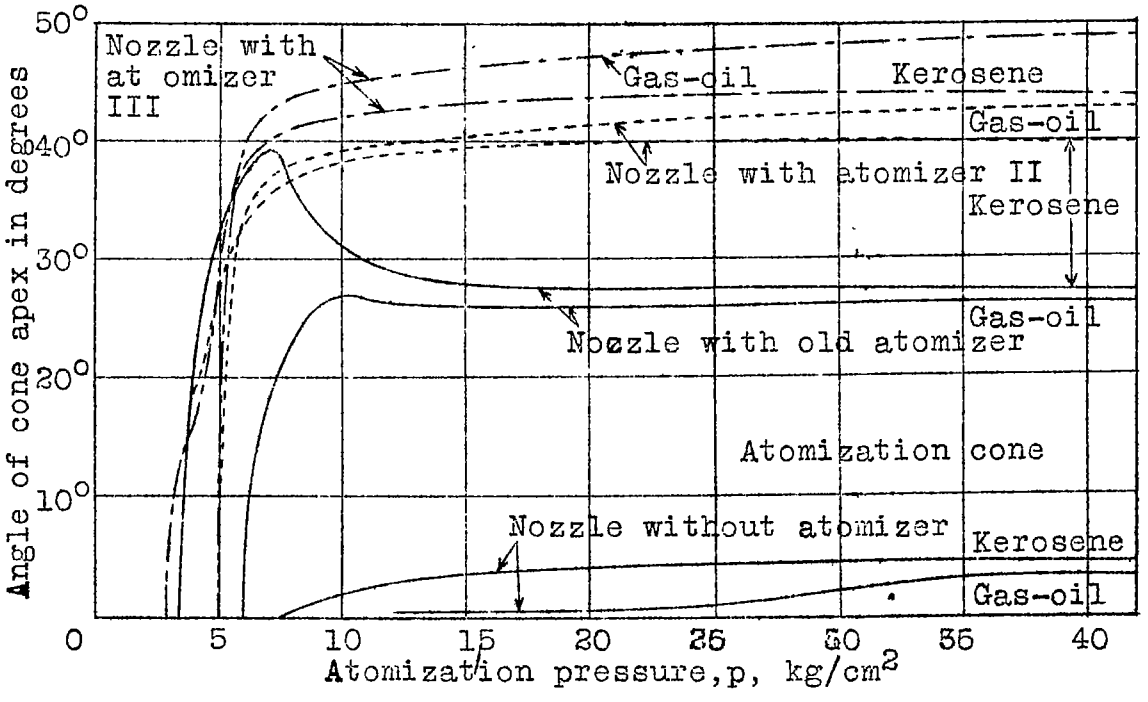


Fig. 23